13th International Symposium on Mach Reflection

Ben Gurion University of the Negev

Beer-Sheva, Israel

June 28 - July 3, 1998

The 13th International Mach Reflection Symposium

Scientific Program & Book of Abstracts

Edited by the Chairman

Professor Gabi Ben-Dor

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JACK H. PEARLSTONE

Jack Pearlstone (1918-1982), whose name the Center bears, was a national leader in real estate development and an activist in community affairs. Yet, he always has time for his fellow human being - he was always there to give a hand where needed.

A native of Dallas, Mr. Pearlstone graduated from Rice University in 1939 and earned a master degree in business administration at Harvard University in 1941.

His illustrious career began in Baltimore where he worked for an aircraft company. He then returned to Dallas, where he was associated with a family grain company until 1951.

Returning to Baltimore, he managed the banking operation of the Joseph Meverhoff Corporation, a real estate development company. In 1960, he was elected the second President of the International Council of Shopping Centers, which he helped found. At the time of his death, he was Chairman of Delta Properties Inc., a Baltimore based national real estate development, investment, and consulting firm. Prior to that, he served as President of Monumental Properties Inc.

Mr. Pearlstone's involvement in community affairs was quite extensive. He served as President of the Associated Jewish Charities and Welfare Fund from 1975 to 1977 and also as President of the Jewish Community Center. He was a member of the boards of the Baltimore Symphony Orchestra, the Lutheran Hospital and Goucher College. He established the Pearlstone School of Graduate Studies at Baltimore Hebrew College and was a guest lecturer on the subject of real estate at several universities.

Mrs. Ann Pearlstone and Mr. Richard Pearlstone of Baltimore, wife and son of the late Jack H. Pearlstone, Jr., through their vision and foresight, have made possible the establishment of the Center for Aeronautical Engineering Studies at the Ben-Gurion University of the Negev.

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Scientific Program

Saturday, 27 June 1998

18:00-22:00: Registration and Welcome Buffet Dinner

Sunday, 28 June 1998

8:30-9:30: Registration (Continuation)

9:30-9:45: Opening Remarks
Professor Gabi Ben-Dor-Chairman, 13th International Mach Reflection Symposium

9:45-10:00: Welcome Regards
Professor Nachum Finger-Rector of the Ben-Gurion University of the Negev

10:00-11:45: Special Session-*Richtmyer-Meshkov Instability*

Chairman: *Kazuyoshi Takayama*

10:00-10:45-**Dov Shvarts** (Invited Lecture)
Recent studies in the nonlinear evolution of Rayleigh-Taylor and Richtmyer- Meshkov instabilities.
10:45-11.15-**Lazhar Houas,** Eugene Meshkov and George Jourdan
An overview of diagnostic methods for studying shock-induced Richtmyer-Meshkov mixing.
11:15-11:45-**Yong Kim**, Conrad Lloyd-Knight, Jae-Chul Oh and John Labenski
Visualization of two-gas interface under shock forcing.

11:45-12:00: Coffee Break

12:00-13:00: Session A1: *Unsteady Shock Wave Reflections*

Chairman: *Charles Needham*

12:00-12:30-**Alex van Netten**
A study on the hysteresis of the regular and Mach reflection of unsteady shock waves.
12:30-13:00-**Beric Skews**, Eugene Timofeev, Peter Voinovich and Kazuyoshi Takayama
The unsteady reflection between two curved shock waves.

13:00-14:00: Lunch

<u>14:00-16:00: Session A2</u>: *Pseudo-Steady Shock Wave Reflections*

Chairman: ***John Dewey***

14:00-14:30-Gabi Ben-Dor, **Ozer Igra** and Lei Wang
Shock wave reflection in dust-gas suspensions.
14:30-15:00-**LeRoy Henderson**, Kazuyoshi Takayama, William Crutchfield and Shigeru Itabashi
Experiment with strong shocks diffracting over rigid ramps.
15:00-15:30-**LeRoy Henderson**, Gabi Ben-Dor, Eugene Vasiliev and Tov Elperin
Jetting in Mach reflection.
15:30-16:00-**Hiroki Honma**. Toshihiro Morioka, Yoshiki Matsuura and Yasuo Suzuki
Radiation observation of Mach reflections of strong shock waves in air.

16:00-16:15-Coffee Break

<u>16:15-18:15: Session A3</u>-*Complex and Weak Shock Wave Reflections*

Chairman: ***LeRoy Henderson***

16:15-16:45-**Kazuyoshi Takayama**, Tsutomo Saito and Eugene Timofeev
Three-dimensional Mach reflection.
16:45-17:15-**Akira Sakurai**
On weak Mach reflections.
17:15-17:45-Akihiro Sasoh and **Kazuyoshi Takayama**
Finite curvature in weak shock wave reflections.
17:45-18:15-**Radhey Shyam Srivastava**
Curvature of a normal shock interacting with a two-dimensional airfoil moving at a supersonic speed.
18:15-18:45-**George Heilig**
Gas dynamic effects on the reflection of short pressure waves over simple structures.

20:00-21:30-Dinner

Monday, 29 June 1998

9:00-9.45: Session B1-***Shock Wave Propagation in Porous Media***

Chairman: ***Beric Skews***

9:00-9:45-Avi Levy (Invited Lecture)
Shock waves interaction with in granular/porous materials.

9:45-10.45: Session B2-***Shock Wave Reflections in Non-Gaseous Media***

Chairman: ***Akira Sakurai***

9:45-10:15-**Shigeru Itoh**, Yoh Nadamitsu, Zhi-Yue Liu and Nasahiro Fujita
Von Neumann reflection of underwater shock wave.
10:15-10:45-**LeRoy Henderson** and Ralph Menikoff
Mach reflection in materials with a convex equation of state.

10:45-11:00: Coffee Break

11:00-13:00: Session B3-***CFD Simulations of Shock Wave Reflections***

Chairman: ***Ozer Igra***

11:00-11:30-Francesco Nasuti and **Marcello Onofri**
Analysis of regular and Mach reflections by a shock fitting technique.
11:30-12:00-**Shen Min Liang**, and Long-Nan Wu
Numerical study of shock wave focusing over parabolic reflections.
12:00-12:30-**Charles Needham**
The importance of Mach reflection in structure loading.
12:30-13:00-**Shmuel Eidelman** and Stephen. Sousk
Use of CFD/CSD simulations for survivability of mine detection equipment.

13:00-14:00-Lunch

14:00-16:00: Session B4-***General shock wave related topics***

Chairman: ***Yong Kim***

14:00-14:30-**Shmuel Eidelman**
Pulse detonation engine: A status review and key issue problems.
14:30-15:00-**John Dewey** and Alex van Netten
Do height-of-burst curves really have knees?
15:00-15:30-**Radhey Shyam Srivastava**
Diffraction of shock waves in monatomic gases.

15:30-22:00-Visit to the Mach Reflection Forest and Mamshit

Tuesday, 30 June 1998

09:00-10:45: Session C1-*Steady Shock Wave Reflections*

Chairman: ***Mikhail Ivanov***

9:00- 9:45-**Gabi Ben-Dor** (Review Lecture)
An overview on the hysteresis phenomena in shock wave reflections in steady flows.
9:45-10:15-**Gabi Ben-Dor**, Tov Elperin, Eugene Vasiliev and Huaidong Li
Downstream pressure induced hysteresis in steady shock wave reflections.
10:15-10:45-**Eduard Golshtein**, Tov Elperin and Gabi Ben-Dor
DSMC simulations of the hysteresis process in shock waves reflection.

10:45-11:00-Coffee Break

11:00-13:00: Session C2-*Steady Shock Wave Reflections (continue)*

Chairman: ***David Zeitoun***

11:00-11:30-**Beric Skews**
Oblique shadowgraph study of shock wave reflection between two wedges in supersonic flow.
11:30-12:00-**Dany Vandromme** and Abdellah Hadjadj
Transition with hysteresis effects between regular and Mach reflection in a 2D supersonic nozzle.
12:00-12:30-**Mikhail Ivanov**, Alexey Kudryavtsev, Gennady Markelov, and Sergei Gimelshein
Numerical studies of three-dimensional effects on the transition between steady regular and Mach reflections.
12:30-13:00-**Mikhail S. Ivanov**, Anatoly Kharitonov and Georgy Klemenkov
Influence of test model aspect ratio in experiments on the RR $\leftrightarrow$ MR transition.

13:00-14:00-Lunch

14:00-16:30: Session C3-*Steady Shock Wave Reflections (continue)*

Chairman: ***Hiroki Honma***

14:00-14:30-Yves Burtschell and **David Zeitoun**
MR $\leftrightarrow$ RR transition in thermodynamically non-equilibrium flows.
14:30-15:00-Sergei Gimelshein, **Mikhail Ivanov** and Gennady Markelov
Real gas effects on shock reflection in steady hypersonic flows.
15:00-15:30-Abdellah Hadjadj, **Dany Vandromme** and Gabi Ben-Dor
Comparison between computational and theoretical results of Li and Ben-Dor on supersonic 2D jets.
15:30-16:00- **Brian Gribben**, K.J. Badcock and B.E. Richards
Numerical study of shock reflection hysteresis in an underexpanded jet.

16:00-16:30-Coffee Break

16:30-18:00: Session C4-*Steady Shock Wave Reflections (continue)*

Chairman: ***Marcello Onofri***

16.30-17.00-**Gregory J. Smolinski** and Ching Shi Liu
An analysis on predicting stem heights in inlet flow Mach reflections.
17.00-17.30- **Brian Gribben**, K.J. Badcock and B.E. Richards
The principle of minimum entropy production applied to inverted Mach reflection and shock reflection hysteresis in steady flow.
17:30-18:00-**Gabi Ben-Dor**, Amer Chpoun and Huaidong Li
Analytical and experimental investigations of the reflection of asymmetric shock waves in steady flows.

18:00-18:30: Closing Session- *Discussion and Conclusions*

Chairman: ***John Dewey***

18:30: Gabi Ben-Dor-Closing Remarks

Recent Studies in the Nonlinear Evolution of Rayleigh-Taylor and Richtmyer-Meshkov Instabilities

Dov Shvarts[1]

Physics Department
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A statistical mechanics model for the bubble and spike fronts evolution from single and multi-mode initial perturbations under the conditions of the Rayleigh-Taylor (RT) and the Richtmyer-Meshkov (RM) instabilities, was developed over the last few years. The basic elements of the model, the single-mode bubble and spike evolution and the two-bubble competition process, have been recently verified in low shock-wave-Mach number shock-tube experiments for a variety of initial conditions and Atwood numbers.

The model has been extended, recently, to include additional scale-lengths in the problem, such as the ablation velocity in an ICF application, the sound speed in compressible fluids and the radius of curvature in non-planar geometries. The changes of the classical power laws in the late time evolution of the bubble front due to the existence of these additional scale-lengths will be discussed.

*In collaboration with:
U. Alon, G. Ben-Dor, L. Erez, G. Erez, L. A. Levin, D. Ofer, D. Oron, O. Sadot, A. Rikanati and Y. Yedvab.

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An Overview of Diagnostic Methods for Studying Shock-Induced Richtmyer-Meshkov Mixing

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Since the last decade, research on the physics of compressible turbulent mixing, and, particularly, experimental shock-tube investigations of the turbulent mixing induced by the Richtmyer-Meshkov instability, have seen the birth of numerous original diagnostic methods and the improvement of many others.

The Richtmyer-Meshkov instability occurs in many engineering domains, e.g., inertial confinement nuclear fusion (mixing of the shell material and the thermonuclear deuterium-tritium during the implosion of a laser target) and supersonic combustion (shock induced mixing of air and hydrogen), as well as in fundamental domains such as astrophysics (supernova explosions). In parallel to the development of numerical hydrodynamic instability turbulence models, scientists were aiming at better understanding the complex flows involved by the use of visualization techniques, and the knowledge of fundamental parameter evolutions within the mixing (density, concentration, etc.), by means of more specific experimental techniques.

The aim of the present paper is to draw up a general picture of the different diagnostic methods for studying shock-induced Richtmyer-Meshkov mixing. The principle of measurement of each technique is summarized, and a general experimental set-up is given to evaluate its basic main difficulties. Then, a table summarizing both the advantages and disadvantages of each diagnostic technique, their technological characteristics and domain of validity, the physical parameters that are measure, the laboratory where it has been developed and an assessment of its mean cost is provided. Of course, each related technique possesses its own financial and technological specificity's, validity domain, as well as optimal running conditions, and leads to the knowledge of different physical parameters. Furthermore, some of them require particular test gases, with adequate spectroscopic characteristics. It is the authors belief that new researchers, and may be, more specialists who need to develop new techniques, could find basic helpful information in the present overview.

Finally, a general presentation of the new large square cross section shock tube that is under construction in our Laboratory, and the diagnostic technique that will be developed as well as the parameters that we hope to determine will be presented.

Visualization of Two-Gas Interface Under Shock Forcing

Yong Kim, Conrad Lloyd-Knight, Jae-Chul Oh and John Labenski

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When metallic targets are exposed to sustained laser excitation at power densities in the range from 10^9 to 10^{11} W/cm^2, plasma plumes with electron density in excess of 10^{21} cm^{-3} and temperature of several hundred electron volts in the core at its peak are produced [1]. In view of the extreme densities involved, we have developed a new diagnostic method in which the plasma dispersion near the critical plasma density is exploited. It entails measurement of attenuation of the exciting laser beam or its second harmonic beam as the beam traverses the plasma along the plasma axis. A pinhole is drilled onto the target at the center for this purpose. In an effort to further increase the plasma temperature and density, we immersed the target in a dense inert gas, such as argon and helium at up to 70 atm. The plasma was compressed and its lifetime increased. However, instability emerged at a critical neutral gas density that scales with the atomic masses of the target element and the ambient gas element. The transmitted intensity of the probing beam exhibits large shot-to-shot fluctuations, suggesting an interfacial instability at the gas-plume interface in the presence of a forcing by the laser beam. The plasma plume is compact and complex in shape, making the visualization of the surface difficult. In order to help delineate whether the instability is of the Rayleigh-Taylor or Richtmyer-Meshkov nature, [2] we have embarked on a shock tube modeling experiment in which a two-gas interface is visualized. A new shock tube has been constructed, capable of producing luminous shock wave. It has a fast action valve incorporating a pair of coupled metallic bellows in lieu of a diaphragm. Full 3D visualization is attempted by means of imaging of the shock luminosity at the contact surface, in addition to usual shock tube diagnostics. The progress to date will be presented.

References

Kim, Y. W. and Park, C. S., (1996), Int. J. Thermophysics, 17, 713.
Baranov, V. Yu., et al, (1993), Phys. Rev. E48, 1324.
Kim, Y. W., (1995), Shock Waves @Marseille I, Eds. Brun and Dumitrescu, 228.

A Study on the Hysteresis of the Regular and Mach Reflection of Unsteady Shock Waves

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Hornung et al. (1979) predicted the existence of a hysteresis between the transition of shock waves from regular and Mach reflection and vice versa within a wind tunnel. Experimental results showing the hysteresis were presented by Ben-Dor (1996) for both the steady wind tunnel reflections and the unsteady reflections of shock waves within a shock tube.

Some of the properties and consequences of this hysteresis effect for the unsteady reflections of shock waves are presented. These are based on the results of a series of numerical experiments using the AWAF code. The AWAF code is an in-house code which uses the weighted average flux (WAF) method (see Toro, 1989) and can solve a variety of hydrodynamic problems. This code was used to solve the problem of a plane shock wave reflecting from a wedge whose surface consists of multiple wedges. The wedge angles are chosen such that at a given Mach number the conditions will provide both regular and Mach reflection on a given single wedge angle depending on the reflection type on the previous surface. The results indicate that, in the dual solution domain, the reflection type can be easily switched between regular and Mach and back by small changes in the wedge surface.

References

Hornung, H. G., Oertel, H., Sandeman, R. J., (1979), "Transition to Mach reflection of shock waves in steady and pseudo-steady flow with and without relaxation", J. Fluid Mech., 90, 541-560.
Ben-Dor, G., (1996), "An Update on the State-of-the-Art of Shock Wave Reflections in Pseudo Steady Flows", 12th Int. Mach Reflection Symp., Johannesburg, South Africa.
Toro, E., (1989), "A weighted average flux method for hyperbolic conservation laws", Proc. Roy. Soc. London, A423, 401-418.

The Unsteady Reflection between Two Curved Shock Waves

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It is known that experimental studies of the reflection of shock waves of solid surfaces are affected by velocity and thermal boundary layers (see Henderson et al. 1997). This results in a delay in the transition from regular to Mach reflection as the angle of incidence of the wave to the surface is increased. To overcome this problem, cavity experiments such as those of Virgona and Higashino (1997), and bifurcated shock tube experiments (Skews 1995), have conducted to remove the effect of the wall. In these cases two plane shock waves are arranged to reflect off each other in free space, with the plane of symmetry then acting as an ideal inviscid and adiabatic surface. These studies show that the transition point is correctly predicted by the von Neumann theory. In view of this success for plane waves, the symmetry technique can now be extended to explore the effect of unsteadiness, using the mutual reflection of two curved shock waves.

The curved shock wave used in this investigation is that of diffraction on a convex corner. This is a highly reproducible phenomenon, with the added advantage that it is pseudo-stationary, with the local shock Mach number and wave angle being constant along any radial line through the corner. A "cookie cutter" is used to slice out the center section of a shock wave propagating down a 360 mm high shock tube, so that two 120 mm high plane waves propagate around the outside of the cookie cutter, diffract around the rear end and reflect off each other at the plane of symmetry. The mutual reflection between them starts off as normal, then is regular, and then undergoes transition to Mach reflection. Since the shape of the diffracting shock for a given Mach number can be simple determined, and thus both the incidence angle and local Mach number can be established, all that is needed to characterize the transition conditions is to measure the position of the radial line through the corner where the reflection changes from regular to Mach reflection.

The experimental measurements were obtained using high-resolution holographic interferometry, with outputs both as interferograms and as shadowgraph to assist in the decision when transition has occurred. Numerical solutions were obtained using an adaptive finite element implementation of the Euler equations. At the present stage of the project spatial resolutions better that 10 microns have been achieved and

there is general agreement between the experimental and numerical studies. Current indications are that the transition does not occur at either the von Neumann or the sonic condition. The experimental studies are being extended to double the resolution and the numerical work is to be taken to 1 micron resolution in order to confirm (and quantify) this finding.

References

Henderson, L. F., Crutchfield, W. Y. and Virgona, R. J., (1997), "The effects of heat conductivity and viscosity of argon on shock waves diffracting over rigid ramps", J. Fluid Mech., 331, 1-36.

Virgona, R.J. and Higashino, F., (1997), "The mutual reflection of shock waves in a cavity", Symposium on Shock Waves, Tokyo-Noko University, Japan.

Skews, B. W., (1995), "Synchronized shock tubes for wave reflection studies", Rev. Sci. Instr. 66, 3327-3330.

Shock Wave Reflections in Dust-Gas Suspensions

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Two of the more investigated shock wave related subjects in the past two decades have been oblique shock wave reflections and shock wave propagation in dust-gas suspensions. These two subjects were summarized in Ben-Dor's (1990) book and Igra & Ben-Dor's (1988) review, respectively.

Surprisingly, to the best of our knowledge, only one paper, a numerical one, (Kim & Chang, 1991) has been published on the combined phenomenon of oblique shock wave reflections in dust-gas suspensions. Unfortunately, their TVD-based numerical study was limited to only one case, a single-Mach reflection (SMR) that resulted from the reflection of a planar incident shock wave having a Mach number $M_0 = 2.03$ over a compressive wedge having an angle $\theta_w = 27°$. They did, however, investigate this case quite thoroughly and conducted a parametric study in which they numerically investigated the influence of the solid particle diameter, D_p, and the loading ratio, η, on the resulted flow field.

The fact that four major shock reflection wave configurations [regular reflection (RR), single-Mach reflection (SMR), transitional-Mach reflection (TMR) and double-Mach reflection (DMR)] are known to exist and the fact that the specific heat capacity of the solid particles, C_s, and their material density, ρ_s, are also known to have an effect on the resulted flow field, motivated us to conduct a comprehensive numerical investigation of the phenomenon.

References

Ben-Dor, G., *Shock Wave Reflection Phenomena*, Springer-Verlag, New York, N.Y., U.S.A., 1991.
Igra, O. and Ben-Dor, G., "Dusty Shock Waves", Applied Mechanics Review, 41(11), 379-437, 1988.
Kim, S-W and Chang, K-S, "Reflection of Shock Wave from a Compression Corner in a Particle-Laden Gas Region", *Shock Waves*, 1(1), 65-73, 1991.

Experiments with Strong Shocks Diffracting over Rigid Ramps

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The experiments were done in argon. An objective was to test prediction made by integrating the N-S equations. This includes the prediction that for ramp angles less than the detachment angle, there is an initial RR that is swept away by an overtaking corner signal which forces the eruption of the MR. We present double exposure holograms that confirm this prediction. However it is found that in the experiments the eruption appears much later than predicted by the numerics and that the Reynolds number has a large effect on the eruption.

Jetting in Mach Reflection

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The phenomenon appears at high shock Mach numbers where the contact discontinuity curls towards the Mach shock. The Mach shock can suffer significant distortion. We present data obtained by integrating the Euler equations. The objective is to obtain a criterion to predict the onset of jetting.

Radiation Observation of Mach Reflections of Strong Shock Waves in Air

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Two-dimensional radiation profiles of Mach reflections in air are observed for strong shock waves passing over a wedge model by using a CCD camera system. A free-piston, double-diaphragm shock tube generates the shock waves. The shocks Mach numbers are about 20 and 25, and the initial pressures are 66.5 Pa and 133 Pa. The wedge angle is fixed at 20 degrees, but rotating the wedge model can change the slope angle. The experiments are carried out for the slope angle 8, 12, 20 and 28 degrees, and compared with the previous result for 16.5 degrees. The reflection type is found to change from the negative double Mach reflection (DMR) to the transitional Mach reflection between the slope angles 8 and 12 degrees as the angle decreases. The kink point and the protrusion of the Mach stem are found for all cases of DMR, in the present experiment. The height of the kink point from the slope surface increases with increase of the slope angle from 12 to 20 degrees, but becomes lower for 28 than for 12. The slight changes are observed for the trajectories of the first triple point and the kink point of the Mach stem by changing the Mach number and the initial pressure.

Three-Dimensional Mach Reflection

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It is still an unresolved problem that the three-dimensional motion of shock waves is a complex extension of a two-dimensional one. Mach reflections, which appear over three-dimensional geometries, do not appear to be merely superposition of the two-dimensional shock wave reflections. So far as three-dimensional shock wave dynamics are concerned, unfortunately experimental approaches are limited and the same is for CFD.

The authors are interested in the motion of three-dimensional shock waves and their Mach reflections and the reflection of planar shock waves from complex geometries.

Shock wave reflections from an oblique cylinder placed in a 100 mm x 180 mm shock tube at Ms = 2.0 in air was examined experimentally and numerically. A detailed comparison between visualization results and numerical ones will be presented.

Findings collected in these comparisons will be applied to interpret the pressure profiles that appear over a three-dimensional volcanic mouth when the volcano explosively erupts and drives a relatively strong blast wave over its mouth.

On Weak Mach Reflection

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The unsteady weak Mach reflection phenomenon, i.e., the so-called von Neumann reflection is considered here. Although the overall feature of the phenomenon can be seen from the results of past experiments and numerical simulations, there have been some renewed interests on its crucial details.

One of them is for the well-defined shapes of shock waves together with the location of the triple point, which are important for the understanding of the nature of the flow field. We examine these with use of the analytical solution of the flow field and the solution of the linearized equation. This approach provides a reasonable answer to the shape of the Mach wave as well as the flow behind it.

Others are concerned mostly with the observations on deviation of the flow field from the self-similar nature. They are such features as the appearance of regular reflection in the initial stage and the change in shock reflection angle at different time stages both to an incident shock wave advancing over an ordinary smooth straight wedge. An adequate cause for these is considered to be the effect of boundary layer behind the advancing shock wave over the wedge surface. The boundary layer theory is utilized to estimate the thickness of the boundary layer. It is found that the thickness grows as $\sqrt{t}$ to the time t compared with t by the overall expansion in the self-similar flow. By admitting that the thicker boundary layer is effectively equivalent to the increase in wedge angle, the effect of the boundary layer to the flow field becomes less in later stages with larger t values in accordance with the observations above.

Finite Curvature in Weak Mach Reflections

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In weak shock wave reflections, the curvature of the incident shock front is finite. The relationship between disturbance propagation mechanisms and the curvature is discussed. The results of a benchmark test on the curvature distribution are presented with investigating the shock front fitting and boundary conditions.

Curvature of a Normal Shock Interacting with a Two Dimensional Airfoil Moving at Supersonic Speed

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Lighthill (1949) solved the diffraction of a normal shock passing over a small bend. Smyrl (1963) considered the interaction of a moving shock with a thin airfoil that is moving with supersonic speed in the opposite direction. Smyrl first solved the interaction of thin infinite wedge and then proposed the theory of thin aerofoil of arbitrary shape. Smyrl gave the pressure distribution on the wedge surface based on Lighthill's linearized theory.

In the present paper an expression for the curvature of the diffracted shock has been derived and numerical results are presented. Srivastava (1994) has included the work of Lighthill and Smyrl and their results have been helpful in completing this new work.

We consider first a plane shock, the plane of which coincides at time t=0 with the (Y, Z) plane moving with velocity U in the direction of the X-axis into a uniform region (0) of still air. A thin wedge of infinite span, whose leading edge coincides at time t=0 with the Z-axis and whose plane of symmetry lies approximately in the (X, Z) plane moves with supersonic speed W in the direction of negative X-axis. We seek a solution for $t > 0$. The main flow regions are shown in figure 1. The Mach number M ($= U/c_0$) and the Mach number M' ($= W/c_0$) of the wedge are the fundamental data defining the problem.

If R is the curvature of the diffracted shock AB (figure 1), the expression for R involving considerable mathematical effort works out to be:

$$\frac{R}{\varepsilon} = \frac{B}{M_1}\frac{1}{y_0^2}(\xi+1)^2 \frac{[K_1(\xi-\xi_1)+K_2(\xi-\xi_2)+K_3(\xi-\xi_1)(\xi-\xi_2)](\gamma_1+\gamma_2)}{[\gamma_2+(\xi-1)][\gamma_1+(\xi-1)](\xi+1)^{1/2}(\xi-\xi_1)(\xi-\xi_2)}$$

B, M_1, y_0, K_1, K_2, K_3, γ_1, γ_2, ξ_1, ξ_2 are functions of M and M'. R/ε has been plotted against $y/y_0 = (\xi - 1/\xi + 1)1/2$ (y is the y coordinate in the physical plane and ξ is the real axis in the final transformed plane). On the diffracted shock, ξ runs from $\xi = 1$ to $\xi = \infty$, so that y/y_0 runs from 0 to 1. R/ε has been calculated first for the combinations M=1.5, M'=2 and M=2, M'=2 to show the effect of varying M for fixed M'. Secondly R/ε has been calculated for the combinations M=2, M'=1.5; M=2, M'=2 and M=2, M'=4 to show the effect of varying M' for fixed M. In both sets of combinations, R/ε maintains negative values from $y/y_0 = 0$, attains a minimum and then rises to a maximum value zero at $y/y_0=1$. For the first set of combinations, the

minimum occurs earlier for M=1.5, M'=2 than for M=2, M'=2. For the second set of combinations the minimum first occurs for M=1.5, M'=2 then for M=2, M'=2, and then M=2, M'=4 in that order. Recently Li and Ben-Dor (1997) have suggested more realistic model than that of Smyrl. However the present investigation is based on Smyrl's model.

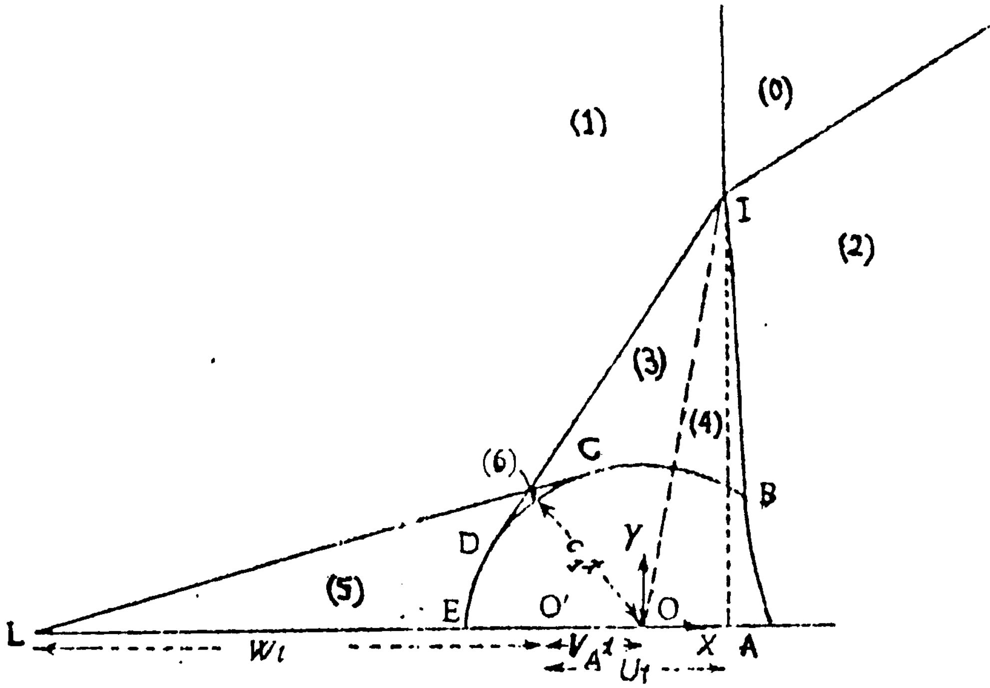

Figure 1: The main flow regions after the wedge has penetrated the shock front.

References
1. Lighthill, M. J., (1949), "The diffraction of blast I", Proc. Roy. Soc., A 198, pp. 454-470.
2. Smyrl, J. L., (1963), "The impact of a shock wave on a two dimensional thin aerofoil moving at supersonic speed", J. Fluid Mech., 15, pp. 223-240.
3. Srivastava, R. S., (1994), *"Interaction of shock waves"*, Kluwer Academic Publishers, The Netherlands.
4. Li, H. and Ben-Dor, G., (1997), "Analytical investigation of two-dimensional unsteady shock-on-shock interactions", J. Fluid Mech., 30, 101-128.

Gas Dynamic Effects on the Reflection of Short Pressure Waves over Simple Structures

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Shock Waves Interaction with Granular/Porous Materials

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The study of the interaction process of shock waves with porous structures and granular materials has been grown intensively in the past decades due to its possible civil and military applications. Often, shock waves will be produced by desired or undesired explosion. The uses of porous or granular material may reduce or increase the maximum amplitudes of the pressure and the solid effective stress. This phenomenon is highly depending upon the solid phase properties and its ability to absorb energy. For example, the survival chances of underground solid structures are strongly depends on the mechanical properties of backpack and backfill materials. In other cases, unusually in the agricultural, chemical and food industries, shock waves may be produced to unblock a blockage silos and pneumatic conveying pipe lines. In these cases, the aim of the shock waves is to break only the particle structures and not the particles themselves. Hence, both particle properties and structure properties (particle-particle interactions, in this case) may influence on the final results. This paper will present the influence of material properties on the shock waves interaction and propagation in porous/granular materials.

Von Neumann Reflection of Underwater Shock Waves

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The von Neumann reflection phenomenon generally appears in the reflection of weak shock wave. Although several investigators have studied this problem, the media that were concerned were gases. Because condensed matter, such as water or metals, usually has much higher sound velocity, it is relatively easy to achieve weak shock waves in it. This paper will report on our investigation on the characteristics of the von Neumann reflection of underwater shock waves. The underwater shock waves are generated by means of detonating stick explosive charges under water. The work includes four parts:

(1) Utilization of streak and framing photography to evaluate the occurrence of the von Neumann reflection of shock waves in water.
(2) Simulation of the reflection process of underwater shock waves by SALE code.
(3) Prediction of the occurrence domains of the von Neumann reflection of underwater shock waves.
(4) Formulation of a theoretical method to determine the structure of the smoothly curved Mach stem in von Neumann reflections.

Mach Reflection in Materials with a Convex Equation of State

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All single-phase materials have a convex equation of state (EOS) for nearly all the thermodynamic states. The only exceptions are high molecular weight fluids in a state close to the critical point. We prove that for a given pressure jump a sequence of two shocks has a smaller entropy jump than a single shock with the same pressure jump. The theorem is applicable to 1-D and 2-D shock interactions including Mach reflections. It is easily extended to N-shocks.

Analysis of Regular and Mach Reflections by a Shock Fitting Technique

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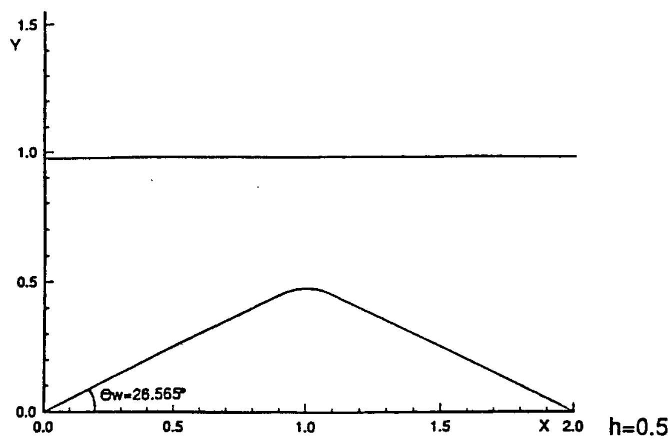
The aim of the paper is to report on the results of a number of numerical tests performed to achieve more insights about the possible hysteresis in the solutions of supersonic flows featuring oblique shock reflections. In particular, transitions between Regular Reflection (RR) and Mach Reflection (MR) have been studied by considering a fixed two-dimensional wedge and a varying oblique shock angle, obtained by means of variations of the free stream Mach number.

Compared to the most common configurations used for these studies, based on the changing of the wedge angle, this approach provides easier numerical solutions not only of the steady state configurations, but also of the real transients from one configuration to another. Indeed, the variation of the angle of the oblique shock can be achieved without requiring the continuous redefinition of the computational grid. Moreover, a double wedge geometry (Fig. 1), which cleans the solution of the effects of the base flow that takes place behind single wedge geometries, has been chosen.



The first set of calculations was devoted to compute steady state solutions for a wedge angle $\Theta_W = 26.55^0$ and Mach number values ranging from 2.5 to 10, along the path shown in Fig. 2. The results are in excellent agreement with the theoretical ones, and have confirmed the existence of a hysteresis of the solution in the dual-solution domain. In particular, as shown in Fig. 4, stable solutions of both RR and MR have been obtained by considering initial conditions displaying RR and MR, respectively.

The second set of tests aimed at analyzing the physical flow evolution between RR and MR by continuously passing through all the possible domains displayed in Fig. 2. A wedge angle of $\Theta_W = 20.5^{\circ}$ was considered, whereas the varying angle of the oblique shock was obtained by varying the free stream Mach number with a cyclical law, as shown in Fig. 3. The results revealed a very good agreement with the theoretical predictions obtained by moving along the relevant line, plotted in Fig. 2. As shown the Fig. 5 (where the location of shock points computed are denoted by a bold dots) the initial MR shock configuration became a RR at $M_0 = 2.90$.

In conclusion, the possibility to predict different configurations in the domain of multiple solution by using a simulation based on a real transient is evident. However, at the same time it is also clear that this approach provides correct flow solutions, that are founded on a physical ground, thus preventing from the uncertainty presented by the steady state approach, which may lead to solutions depending on the initial conditions assumed.

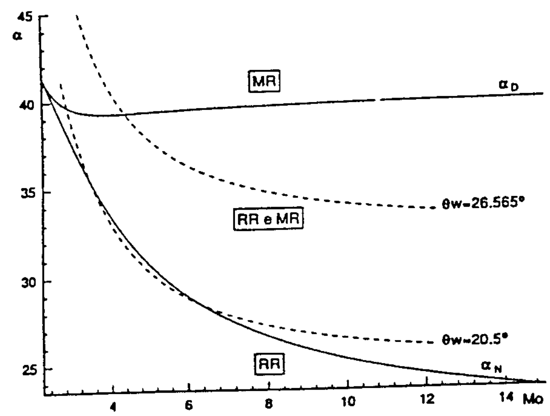


Fig. 2

Transitorio con periodo di 200000 iterazioni

(θ_w=20.5°, h=0.41, reticolo 68x42):

$M_0=7.5+4.8\sin\{[(k-52500)/200000]2\pi\}$

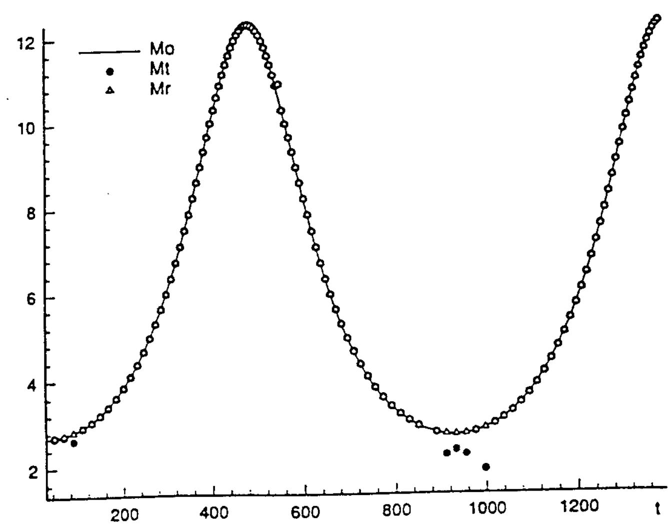
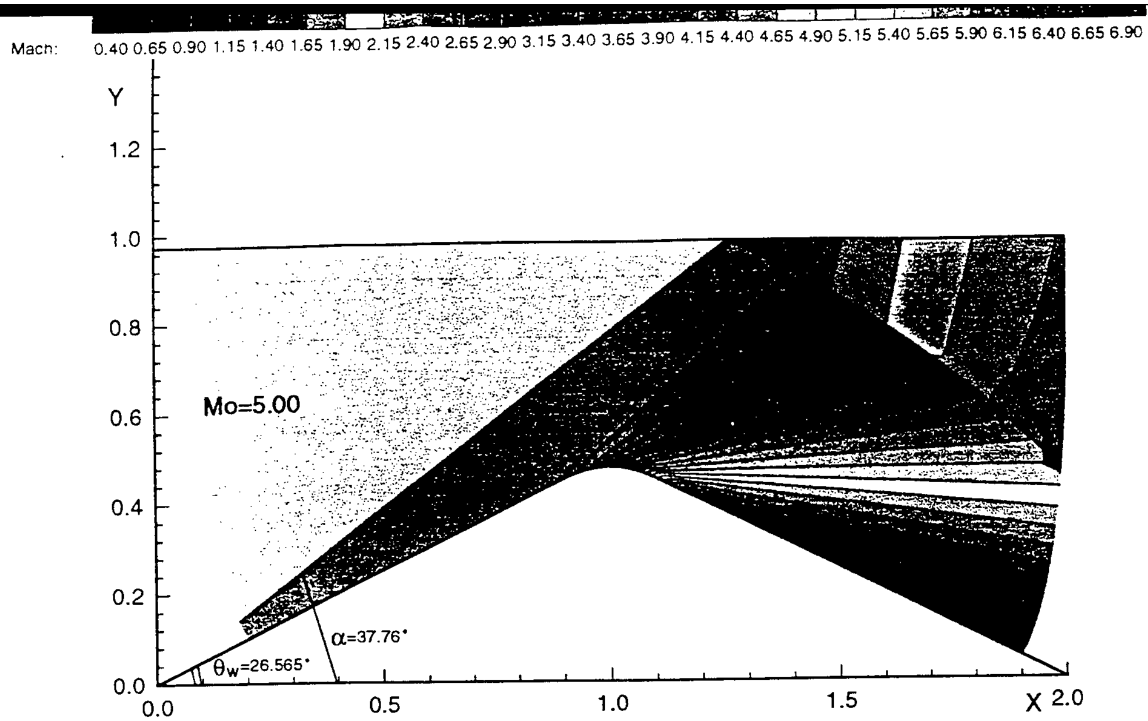
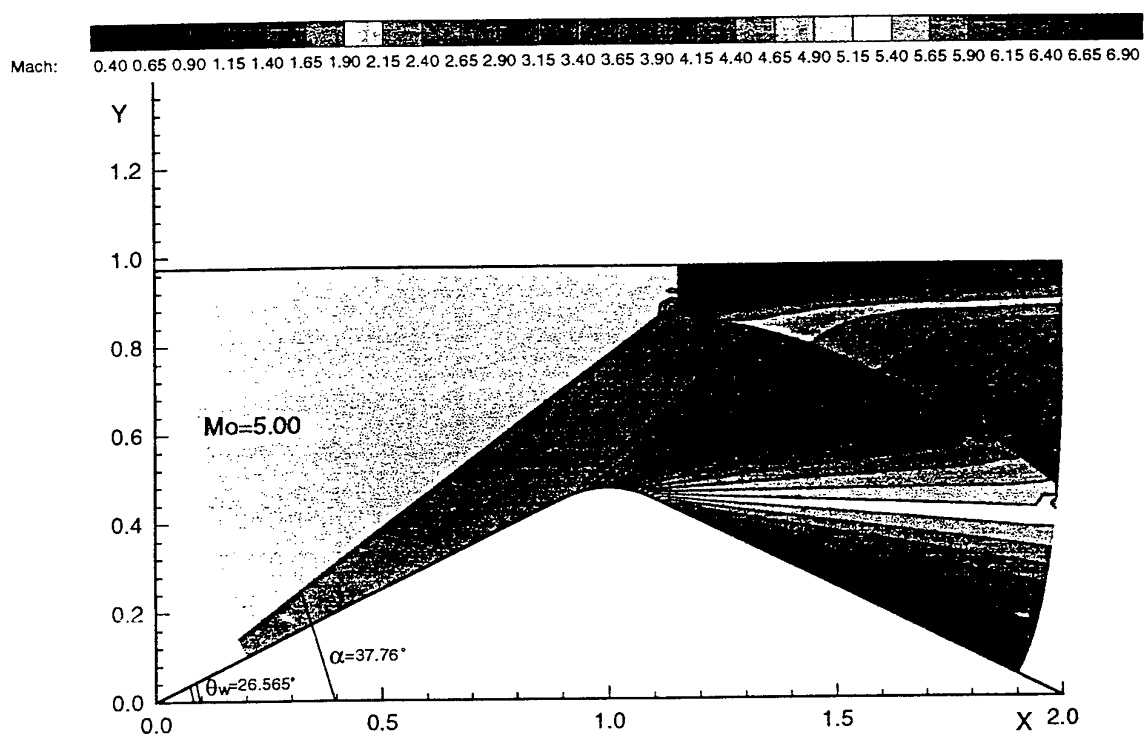


Fig. 3



Mach: 0.40 0.65 0.90 1.15 1.40 1.65 1.90 2.15 2.40 2.65 2.90 3.15 3.40 3.65 3.90 4.15 4.40 4.65 4.90 5.15 5.40 5.65 5.90 6.15 6.40 6.65 6.90
Y
1.2
1.0
0.8
0.6
0.4
0.2
0.0
Mo=5.00
α=37.76°
θw=26.565°
0.0
0.5
1.0
1.5
X 2.0

(a)



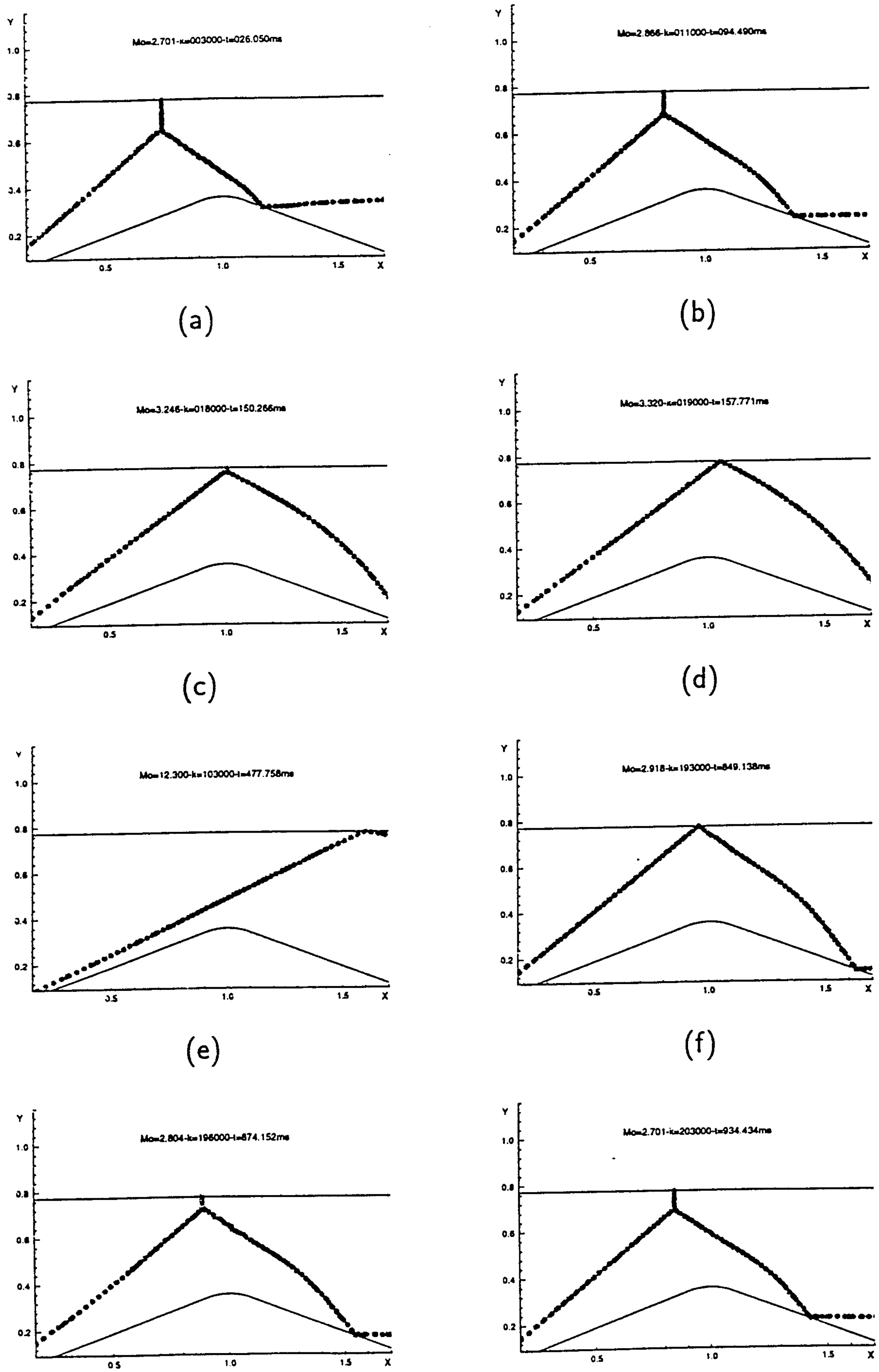
Mach: 0.40 0.65 0.90 1.15 1.40 1.65 1.90 2.15 2.40 2.65 2.90 3.15 3.40 3.65 3.90 4.15 4.40 4.65 4.90 5.15 5.40 5.65 5.90 6.15 6.40 6.65 6.90
Y
1.2
1.0
0.8
0.6
0.4
0.2
0.0
Mo=5.00
α=37.76°
θw=26.565°
0.0
0.5
1.0
1.5
X 2.0

(b)

Fig. 4

FIG. 5

Evoluzione della configurazione degli urti causata dalla variazione di M_0 transizioni: MR⇒RR a M_0=3.32, RR⇒MR a M_0=2.90.



(g) (h)

Numerical Study of Shock Wave Focusing over Paraboloidal Reflectors

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The problem of an incident plane shock wave propagating in air over paraboloidal reflectors is numerically investigated. A Navier-Stokes solver was developed by an improved, implicit, upwind total variation diminishing (TVD) scheme in a finite-volume approach. Real-gas effects were taken into account if high temperature occurred. The solver was validated on four test problems. The complex flow fields of shock wave focusing for reflectors with different depths at various incident shock wave Mach numbers were studied. An interesting result of a maximum pressure occurring at the reflector center was found. This was due to the occurrence of an implosion phenomenon. A maximum temperature might occur at the reflector center or at other locations, depending on the flow conditions and the reflector depth. Moreover, vortical flows caused by shock wave focusing and their formation mechanism were explored. It was found that the vortices near the reflector were caused by an additional shock/slipline interaction. Due to the high-pressure formation at the reflector center and the sliplines at the symmetry axis, a jet flow could be induced. The jet flow resulted in other vortices near the focal region.

The Importance of Mach Reflections in Structure Loading

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At previous Mach reflection symposia we have shown that the Mach stem and triple point play an important role in the pressure and impulse loads on a structure. This paper expands on the dominant role played by Mach reflection in exterior and interior load definition. The loads are supplied by the air blast resulting from the detonation of various shapes and sizes of explosive charges. The detonations may be interior or exterior to the structures. As the triple point sweeps across the face of a wall, floor or ceiling, the pressure and impulse show sharp differences delineated by the path of the triple point. We also show how Mach reflections may play an important role in shear failures of structural components, such as supporting walls.

Recent ARA SHARC calculations include the CONDO test at Eglin AFB, our calculations supporting the Al Kohbar towers incident of June 1996 and predictive calculations for anti-terrorism structure tests. Several examples of two and three-dimensional air blast load calculations will be presented. Where possible, comparisons with experimental data will be made.

This work was sponsored by the Defense Special Weapons Agency (DSWA) in Alexandria, Virginia and the U.S. Air Force Wright Laboratory, Armament Directorate, Munitions Division, Studies and Analysis Branch.

Use of CFD/CSD Simulations for Survivability Analysis of Mine Detection Equipment

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Mine Detection systems will operate in a mine field environment and will identify various AT and AP mines which will be subsequently detonated at different distances from the system. System survivability during a mine clearing operation (which includes ensuring platform mobility and unimpeded sensor operation) is one of the most important factors in defining its performance. Current mine detection systems concepts require to detect mines at close distance and to place neutralization device in the vicinity of the mine. This mode of operation leads to additional risk of triggering a mine in a very close proximity to detection system, which leads to increases demands to protection levels required for various electronic systems survivability.

SAIC has developed and integrated a set of numerical tools that enable analysis of the mine blast, blast interaction with a complex three dimensional structures, and structural response to blast loads. These codes (MPHASE, SOG2D, AUGUST3, FELISA, GRIDTOOL, DYNA3D) where extensively validated for problems of explosives detonation and blast structure interaction and were used for survivability analysis and design of blast protective devices. Use of these developed and validated analysis tools will allow accurate assessment of the Mine detection system vulnerability in its designed mode of operation and will enable development of blast protection methods for specific elements of the system.

References

1. Eidelman, S., Lottati, I. and Yang, X., "Development of Mine-Resistant Vehicles," SAIC Report 93/1141, 1993.
2. Baker T. J. and Jameson, A., "A Novel Finite Element Method for the Calculation of Inviscid Flow Over a Complete Aircraft," 6th International Symposium on Finite Element Methods in Flow Problems, Antibes, France, 1986.
3. Baker, T. J., "Developments and Trends in Three-Dimensional Mesh Generations," Transonic Symposium held at NASA Langley Research Center, Virginia, USA, 1988.
4. Lottati, I., Eidelman, S. and Drobot, A., "A Fast Unstructured Grid Second Order Godunov Solver (FUGGS)," 28th Aerospace Sciences Meeting, AIAA-90-0699, Reno, NV. USA, 1990.
5. Lottati, I. Eidelman, S. and Drobot, A., "Solution of Euler's Equations on Adaptive Grids Using a Fast Unstructured Grid Second Order Godunov Solver," Proceeding of the Free Lagrange Conference, Jackson Lake, WY, USA, 1990.
6. Lottati, I. and Eidelman, S., "Second Order Godunov Solver on Adaptive Unstructured Grids," Proceeding of the 4th International Symposium on Computational Fluid Dynamics, Davis, CA, USA, 1991.
7. Eidelman, S. Collela, P. and Shreeve, R. P., "Application of the Godunov Method and Its Second Order Extension to Cascade Flow Modeling," AIAA J. 22(10), 1984.

8. Lottati I. and Eidelman, S., "Blast and Structural Simulation/Analysis for Development of a Centerline Blast Deflector for the Cab of an M923A2, 5-Ton Cargo Truck," SAIC Final Technical Report, 1994.

9. Eidelman S. and Lottati, I., "Blast Simulation and Analysis," SAIC Report, 1994.

10. Lottati I. and Eidelman, S., "Blast and Structural Simulation/Analysis for Development of an Off-Centerline Blast Deflector for the Cab of an M923A2, 5-Ton Cargo Truck," SAIC Report, 1995.

11. Lottati I. and Eidelman, S., "A Second-order Godunov Scheme on a Spatial Adapted Triangular Grid," Applied Numerical Mathematics, 14, 353-365, 1994.

Pulse Detonation Engine: A Status Review and Key Research Issues

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With no moving parts in the power production section and its thermodynamically efficient cycle, the Pulsed Detonation Engine (PDE) offers a low cost alternative to turbojet and liquid-propellant rocket engines. Both air breathing and pure rocket modes of engine operation offer substantial system, materials, and cycle advantages that will allow us to bypass the scalability, operational range, efficiency, and cost limitations of existing engines. We introduced the modern PDE concept in 1986 and experimentally demonstrated its operation in 1986 and 1994. The concept was subsequently studied extensively in a number of analytical and experimental studies. The Pulsed Detonation Engine is now recognized as the most promising propulsion concept for aerospace transportation in the next century. The knowledge gained in recent experimental studies and the level of understanding gained through extensive CFD simulations of the PDE cycle will allow us to progress to the next steps of engine development.

This article reviews the current status of the PDE concept; it gives an overview of classes of engines where the PDE concept provide advantages over existing engines or open a new scale or performance range. We will also review some key issues to be resolved for successful PDE implementation and outline the PDE technology development road map for the next stages of engine development.

An air-breathing version of PDE will provide a low cost alternative to existing jet engines for a number of applications. In Table 1 we illustrate how specific properties of PDRE technology result in engine performance or vehicle system advantages compared with existing systems.

To realize these advantages, a number of diverse well-funded R&D efforts should be initiated to develop and analyze PDE performance at different scales and operational conditions. In addition, these efforts should be accompanied by an extensive research program to address a number of basic issues in PDRE implementation such, as initiation, fuels, cycle analysis, and structural analysis

PDRE Characteristics	Advantage	Engine Performance Improvement
High cycle efficiency	Efficient constant volume unsteady cycle. Direct thrust generation.	Increase payload and reduce cost for lunar and planetary excursion vehicles
Hybrid mode using atmospheric air and oxygen at high altitude	Same engine volume can be used for air/fuel or oxygen/fuel detonations	Reduce cost of ETO transportation as a result of expected 2000 sec I_{sp} in air
High structural efficiency	Simple nonmoving parts design. No need for turbines and compressors	Reduce system cost and increase reliability.
No exotic materials or technologies needed for operation	Low thermal load due to intermittent cycle. Uses conventional fuels.	Simple fabrication methods and materials will result in space propulsion systems produced using manufacturing methods similar to automotive technology at low cost.
Vector thrust from an array of PDREs.	Simple device with no geometrical constraints can be integrated into an array. Every cycle controlled separately.	High maneuverability. Reduces number of propulsion systems since one engine can be used for both power generation and trajectory corrections.
Variable power generation from 0 to Max	Independent generation of every cycle and full control over cycle frequency.	Optimized propulsion system achieved by matching power output to mission requirements.
Scalability from less than 1 lb to more than 100,000 lb thrust	Simple design. Ease of integration of multiple sections. Operation cycle feasible for a wide range of conditions and engine sizes.	Revolutionary technology applicable to a wide range of engine classes.

Table 1. Specific properties of the PDE technology

References

1. Eidelman, S., Grossmann, W., Gunners, N. -E. and Lottati, I., "Progress in Pulsed Detonation Engine Development," AIAA-94-2721, Indianapolis, IN, USA, 1994.
2. Helman, D., Shreeve, R. P. and Eidelman, S., "Detonation Pulse Engine," AIAA-86-1683, 2nd Joint Propulsion Conference, Huntsville, 1986.
3. Eidelman, S., Grossmann, W. and Lottati, I., "Propulsion Applications of the Pulsed Detonation Engine Concept," SAIC Report Number 89/1684, 12/ 31, 1989.
4. Eidelman, S. and Grossmann, W., "Computational Analysis of Pulsed Detonation Engines and Applications," AIAA-90-0460, Reno, Nevada, USA, 1990.
5. Eidelman, S., Grossmann, W. and Lottati, I., "Air-Breathing Pulsed Detonation Engine Concept; A Numerical Study," AIAA-90-2420, Orlando, FL, USA, 1990.
6. Eidelman, S., et al., "A Review of Propulsion Applications of the Pulsed Detonation Engine Concept," J. Propulsion and Power, 7(6), 857-865, 1991.

7. Eidelman, S., et al., "Pulsed Detonation Engine Experimental and Theoretical Review," AIAA-92-3168, AIAA/ASME 28th Joint Propulsion Conference, Nashville, TN, USA, 1992.
8. Eidelman, S., et al., "A Parametric Study of the Air-Breathing Pulsed Detonation Engine," AIAA-92-0392, Reno, Nevada, USA, 1992.
9. Eidelman, S., Yang, X. and Lottati, I., "Pulsed Detonation Engine: Key Issues," AIAA-95-2754, AIAA/ASME 31st Joint Propulsion Conference, San Diego, LA, USA, 1995.

Do Height-of-Burst Curves Really Have Knees?

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When an explosive is detonated at some height above the ground surface it produces a spherical blast wave which interacts with the ground. Immediately under the center of the explosion, at ground zero (GZ), the shock front is normal to the ground. As the shock expands, the angle of incidence with the ground increases and a regular reflection (RR) is produced. Beyond a limiting angle of incidence there is a transition to a Mach Reflection (MR). The physical properties of the blast wave, such as peak hydrostatic overpressure, vary with distance from GZ, and for a given charge size, also depend on the height-of-burst (HOB). The variation of a specific blast property, such as 1 atm hydrostatic overpressure, can be plotted in the HOB - ground range plane, for a unit charge size. Such a curve is called a height-of-burst curve.

The peak pressure immediately behind the reflected shock of an RR can be calculated using the von Neumann 2-shock theory. For intermediate and low shock strengths, this theory predicts a significant increase of pressure just before transition to MR, and this increase has a large effect on the HOB curve, giving it a pronounced knee. This is interpreted to mean that there are high overpressures at unexpectedly large distances from GZ, and that the overpressures in some regions may increase rather than decrease with distance. In order to predict the hazards from a HOB explosion it is important to know if the knees on the HOB curves do exist.

With one possible exception, the theoretically predicted pressure increase has not been observed on field tests with air burst explosions of charge sizes ranging from 5 kg to 200 tons. It has not been observed in laboratory experiments with charges of 0.5 g. In shock tube experiments, in which plane shocks are reflected from plane rigid wedges, pressure increases have been observed close to the conditions for transition to MR. However, this condition, in which the shock strength and angle of incidence are both constant, is different from that of a HOB explosion for which both the shock strength and angle of incidence are continuously changing. This latter condition can be simulated in a shock tube using a uniform plane shock reflecting from a curved surface, and several workers have failed to show any pressure increase in such a case.

The problem can also be studied using numerical simulation techniques. Such simulations predict an increase of pressure, but not of the same magnitude as predicted by the 2-shock theory. Also the level of pressure increase is dependent on the grid spacing used in the simulation. The results of such numerical simulations will be shown, and those from recent shock tube experiments using a curved reflecting surface with a large radius of curvature, and an experimental pressure gauge with a very small surface area. The experiments show an increase of pressure just before transition, and the type of pressure profile is similar to that predicted by a numerical simulation with a course grid. So do HOB curves have knees? The authors do not wish to answer that question at this time because the answer may change between the time of writing this abstract and presenting the paper.

Diffraction of Shock Waves in Monatomic Gases

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Lighthill (1949) considered the diffraction of a normal shock wave past a small bend. Whitham (1957) developed an approximate theory for diffraction of shock waves and compared some of his results with those of Lighthill. Srivastava (1963) extended the work of Lighthill for monatomic gases. In the present paper Whitham's approximate theory has been used for monatomic gases and some of the new results have been compared with those of Srivastava (1963).

Firstly Chester's (1954) function has been calculated for different Mach numbers as it forms important part in the analysis of Whitham's theory. The Chester function is given by

$$K(M_0) = 2\left\{\left[1+\frac{2(1-\mu^2)}{(\gamma+1)\mu}\right]\left(2\mu+1+M_0^{-2}\right)\right\}, \quad \mu^2 = \frac{(\gamma-1)M_0^2+2}{2\gamma M_0^2-(\gamma-1)} \tag{1}$$

In (1) M0 is the Mach number and γ is the ratio of specific heats.

For the computation γ has been taken to be equal to 5/3. For this value of γ, $K(M_0)=0.5$ when $M_0=1$ and $K(M_0)=0.4509$ as $M_0 \to \infty$. For $\gamma=1.4$, $K(M_0)=0.5$ when $M_0=1$ and $K(M_0)= 0.39414$ as $M_0 \to \infty$. We notice here that Chester's function $K(M_0)$ shows smaller decrease (from 0.5 to 0.45089) when $\gamma = 5/3$ than when $\gamma = 1.4$ (from 0.5 to 0.39414).

Secondly the angle formed by the wall and the line joining the corner of the bend point of intersection of the Mach circle and the normal shock after diffraction has been calculated for different Mach number. The angle referred to is actually m_0 of figure 1. The angle m_0 could be obtained directly or by the application of Lighthill's theory. The calculated values of m_0 were compared with the m_0 given by Whitham's theory. Skews (1967) has carried out this problem theoretically and experimentally for $\gamma = 1.4$. The angle m_o is given by

$$\tan m_0 = \frac{\sqrt{1-k^2}}{k} = \frac{(\gamma-1)(M_0^2-1)\left\{M_0^2+\frac{2}{(\gamma-1)}\right\}}{(\gamma+1)M_0^4} \tag{2}$$

where $k = (U - V_1) / a_1$, U being the shock velocity, V_1 is the flow behind the normal shock and a_1 is the sound speed behind the normal shock.]

For $\gamma = 5/3$:

$$\tan m_0 = \frac{(M_0^2 - 1)(M_0^2 + 3)}{4M_0^4} \tag{3}$$

and Whitham's theory gives

$$\tan m_0 = \frac{(M_0^2 - 1)K(M_0)}{2M_0^2} \tag{4}$$

where $K(M_0)$ has already been discussed earlier. M_0 versus m_0 from equation (3) and M_0 versus m_0 from equation (4) have been plotted for M_0 varying from 1 to ∞. For $M_0 \to \infty$, $m_0 = 26.56^\circ$ from (3) and m0 = 25.39° from equation (4). We observe that there is more closeness in the value m_0 when $M_0 \to \infty$ for $\gamma = 5/3$ than for $\gamma = 1.4$.

We would give other important results. Whitham obtained for a shock diffracting around a small bend the relation

$$M_w - M_0 = \theta_w \left\{ \frac{1}{2}(M_0^2 - 1)M(M_0) \right\}^{1/2} \tag{5}$$

where M_w is the shock Mach number at the wall, M_0 is the shock Mach number, θ_w is the small bend angle. For weak shocks, relation (5) becomes

$$M_w - M_0 \approx \theta_w \left\{ \frac{1}{2}(M_0^2 - 1) \right\}^{1/2} \tag{6}$$

Lighthill gets $8/3\pi$ of the value given on the right hand side of equation (6). For $\gamma = 5/3$ the same relation as (6) holds and also Lighthill's theory for $\gamma = 5/3$ predicts the same multiplying factor $8/3\pi$ on the right hand side of (6).

For strong shocks Whitham obtains for $\gamma = 1.4$

$$M_w - M_0 \approx 0.4439 M_0 \theta_w \tag{7}$$

Lighthill's value has to be obtained from a graph and one can only say that the numerical factor in equation (7) is less than 0.5. For $\gamma = 5/3$, using the results of Srivastava, one obtains,

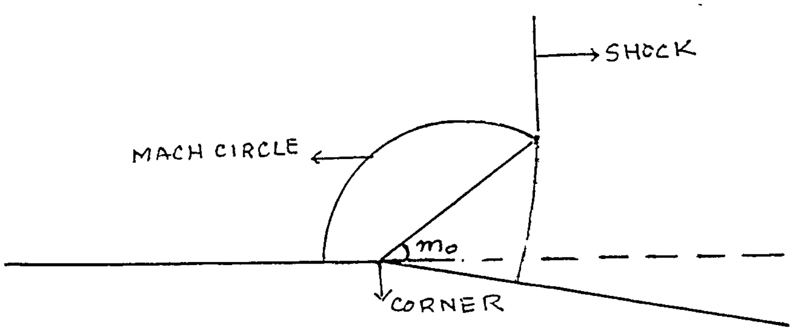
$$M_w - M_0 \approx 0.5 M_0 \theta_w \tag{8}$$

Whitham's theory for strong shocks $(\gamma = 5/3)$ gives

$$M_w - M_0 \approx 0.4761 M_0 \theta_w \tag{9}$$

From equations (8) and (9) we find that the results are quite close.

Finally diffraction around a bend of 90° for $\gamma = 5/3$ has been worked out by the application of Whitham's theory.



References

1. Lighthill, M. J., (1949), Proc. Roy. Soc., A 198, pp. 454-470.
2. Whitham, G. B., (1957), J. Fluid Mech. 2, pp. 145-171.
3. Srivastava, R. S., (1963), British Aero Res. Council C. P. No. 603.
4. Chester, W., (1954), Phil. Mag. 45, 1293.
5. Skews, B. W., (1967), J. Fluid Mech. 29, 2, pp. 297-304.

Hysteresis Phenomena in Shock Wave Reflections in Steady Flows

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Ernst Mach first studied the shock wave reflection phenomenon more than a hundred years ago. He recorded experimentally two different shock wave reflection configurations. The first, a two-shock wave configuration, was named regular reflection, RR, and the second, a three-shock wave configuration, which was first named irregular reflection, IR, was later re-named and is known today as Mach reflection, MR.

The RR wave configuration consists of two shock waves: the incident, i, and the reflected, r, shock waves. They intersect at the reflection point, R, which is located on the reflecting surface. The MR wave configuration consists of three shock waves: the incident, i, the reflected, r, and the Mach stem, m, shock waves and one slipstream, s. They all intersect at a single point, the triple point, T.

The analytical models for describing the RR and the MR wave configurations were initiated, in the early 1940s, by von Neumann. They are known as the two- and three-shock theories, respectively. Both theories make use of the conservation equations across the shock waves together with appropriate boundary conditions.

Two extreme criteria, α_N - the von Neumann criterion and α_D - the detachment criterion[1], at which the RR $\leftrightarrow$ MR transition can occur are known. Theoretically, RR is not possible for $\alpha > \alpha_D$ and MR is not possible for $\alpha < \alpha_N$. In the range $\alpha_N \leq \alpha \leq \alpha_D$ both RR and MR types are theoretically possible, for this reason this range is known as the dual solution domain.

The existence of the dual solution domain led, in the early 1980s, to the hypothesis that a hysteresis can exist in the RR $\leftrightarrow$ MR transition[2]. However, since no experimental evidence of this hypothesis was reported[3], it was believed that the RR in the dual solution domain is unstable.

Based on the principle of minimum entropy production it was shown analytically[4], in the mid-1990s, that the RR wave configuration is stable in the dual solution domain. Soon after, the hysteresis phenomenon in the RR $\leftrightarrow$ MR transition was recorded experimentally for the first time[5]. Then the existence of both RR and MR wave configurations in the dual solution domain [for the same flow Mach numbers, M_0, and the reflecting wedge angles, θ_w, but different distances from the line of

symmetry] was demonstrated numerically[6] using an FCT based algorithm. Following these studies numerical simulations based on the DSMC method[7-9] and the TVD algorithm[6,10] demonstrated the above mentioned hysteresis phenomenon, for identical initial conditions, for the first time.

Owing to the above mentioned studies detailed analytical and numerical investigations were conducted in order to better understand the parameter affecting the shock wave reflection in steady flows, in general, and the hysteresis process, in particular. Among the various results of these investigations a pressure-induced hysteresis, which has never been reported before, was discovered[11]. Many more details and results will be provided in the presentation.

References

1. Ben-Dor, G. (1991), *Shock Wave Reflection Phenomena*. Springer-Verlag, New York.
2. Hornung, H. G., Oertel, H. Jr., and Sandeman, R. J. (1979), "Transition of Mach reflection of shock waves in steady and pseudosteady flow with and without relaxation", J. Fluid Mech., 90, pp. 541-560.
3. Hornung, H. G. and Robinson, M. L. (1982), "Transition from regular to Mach reflection of shock waves. Part 2 The steady flow criterion," J. Fluid Mech., 123, pp. 155-164.
4. Li, H. and Ben-Dor, G. (1996), "Application of the principle of minimum entropy production to shock wave reflections. Part 1. Steady flow," J. Appl. Phys., 80(4), 2027-2037.
5. Chpoun, A., Passerel, D., Li, H. and Ben-Dor, G. (1995), "Reconsideration of oblique shock wave reflection in steady flows. Part I: Experimental investigation," J. Fluid Mech., 301, pp. 19-35.
6. Vuillon, J., Zeitoun, D. and Ben-Dor, G. (1995), "Reconsideration of oblique shock wave reflection in steady flows. Part II: Numerical investigation," J. Fluid Mech., 301, pp. 37-50.
7. Ivanov M. S., Gimelshein S.F. and Beylich A. E. (1995), "Hysteresis effect in stationary reflection of shock waves," Phys. Fluids, 7 (4), pp. 685-687.
8. Ivanov, M. S., Zeitoun D., Vuillon J., Gimelshein S.F. and Markelov G. (1996), "Investigation of the hysteresis phenomena in steady shock reflection using kinetic and continuum methods," Shock Waves, 5, pp. 341-3469.
9. Ben-Dor, G., Elperin, T. and Golshtein, E. (1997), "Monte-Carlo analysis of the hysteresis phenomenon in steady shock wave reflection," AIAA J., to be published.
10. Shirozu, T. and Nishida, M. (1995), "Numerical studies of oblique shock reflection in steady two-dimensional flows," Memoirs of the Faculty of Engineering, Kyushu University, Fukuoka, Japan, 55(2), pp. 193-204.
11. Ben-Dor, G., Elperin, T. and Vasiliev, E. (1997), "Downstream Pressure Induced Hysteresis in the Regular ⇔ Mach Reflection Transition in Steady Flows", Physics Fluids, to be published.

Downstream-Pressure Induced Hysteresis in Steady Shock Wave Reflection

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The effect of the downstream-pressure[2] on the shock wave reflection in steady flows is investigated both numerically and analytically. The dependence of the shock wave configurations on the downstream-pressure is studied. In addition to the incident-shock- wave-angle-induced hysteresis, which was discovered a few years ago, a new downstream-pressure-induced hysteresis has been found to exist. The numerical study reveals that when the downstream-pressure is sufficiently high, an inverse-Mach reflection wave configuration, which has so far been observed only in unsteady flows, can be also established in steady flows. Very good agreement between the analytical predictions and the numerical results is evident.

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[2] The term downstream pressure, in this study, does not refer to the pressure downstream on the center line but to the wake pressure behind the tail of the reflecting wedge.

Monte Carlo Analysis of the Hysteresis Phenomenon in Steady Shock Wave Reflections

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Ernst Mach was the first to study the shock wave reflection phenomenon. More than a hundred years ago, he recorded experimentally two different shock wave reflection configurations, a regular reflection (RR) and a Mach reflection (MR). Intensive research of the reflection phenomenon of shock waves was re-initiated in the early 1940's by von Neumann. Since then it has been realized that the MR wave configuration can be further divided into more specific wave structures[1].

The analytical models for describing the RR and the MR wave configurations were initiated by von Neumann. They are known as the two- and three-shock theories, respectively. Both theories make use of the conservation equations across the oblique shock waves together with appropriate boundary conditions.

Two extreme angles, α_N - the von Neumann angle and α_D - the detachment angle[1], at which the $RR \leftrightarrow MR$ transition can occur are known. Theoretically, RR is not possible for $\alpha > \alpha_D$ and MR is not possible for $\alpha < \alpha_N$. In the range $\alpha_N \le \alpha \le \alpha_D$, which is known as the dual solution domain, both RR and MR are theoretically possible.

The existence of the dual solution domain led, in the early 1980's, to the hypothesis that a hysteresis can exist in the $RR \leftrightarrow MR$ transition[2]. A following experimental study[3] failed to record the hysteresis phenomenon. The fact that no experimental evidence of this hypothesis was reported, was attribute to the belief that the RR is unstable in the dual solution domain.

Based on the principle of minimum entropy production in was shown analytically[4], in the mid 1990's, that the RR is stable in the dual solution domain. Soon after, the hysteresis phenomenon in the $RR \leftrightarrow MR$ transition was recorded experimentally for the first time[5]. Then the existence of both RR and MR in the dual solution domain [for the same flow Mach number, M_0, and reflecting wedge angle, β, but different values of g] was demonstrated numerically[6] using an FCT based algorithm. Following these studies numerical simulations based on the DSMC method[7,9] and the TVD algorithm[8,9] demonstrated the hysteresis phenomenon for the first time. The theoretical, experimental and numerical $RR \rightarrow MR$ and $MR \rightarrow RR$ transition angles for M_0=4.96 as obtained in the studies are summarized in Table 1. It is evident from Table 1 that while the experimental[5] value of $\alpha(MR \rightarrow RR)$ is identical to the theoretical one, the experimental value of $\alpha(RR \rightarrow MR)$ is more than 2° smaller than the theoretical one. The reason for this could be attributed to 3-D effects in the

experiment. An opposite situation is obtained when the numerical[7] values are considered. Now the numerical value of $\alpha(\mathrm{RR} \to \mathrm{MR})$ is very close to the theoretical one and the numerical[7] value of $\alpha(\mathrm{MR} \to \mathrm{RR})$ is 5.6° larger than the theoretical one.

The DSMC based numerical method used by Ivanov et al.[7] enabled one to account for the gas viscosity and the finite thickness of the shock waves. Unfortunately, however, the DSMC computations of flows with Knudsen numbers $\mathrm{Kn} \leq 0.005$ which are fairly close to the continuum regime ($\mathrm{Kn}=\lambda / \mathrm{L}$, where λ is the mean free path in the free stream and L is the length of the wedge, see Fig. 1a) are time consuming.

While in their calculations an adaptive grid was used, in our simulations a rectangular domain and rectangular grid with a constant cell size (about one mean free path) were used. The hard sphere model was adopted for molecular collisions simulation where the energy exchange between the translational and the rotational modes was described by the Larsen-Borgnakke model[10]. Note that the results of the transition angles $[\alpha(\mathrm{RR} \to \mathrm{MR}), \alpha(\mathrm{MR} \to \mathrm{RR})]$ obtained with the variable hard sphere model[10] (VHS) and those obtained using the hard sphere (HS) model are practically the same. Owing to symmetry only one half of the computational domain was considered and specular reflection was assumed at the symmetry plane. Free stream conditions with a Maxwellian distribution function were assigned at the upstream boundary. Since the oncoming flow was supersonic, vacuum boundary conditions could be used as the downstream boundary conditions whereby molecules that left the computational domain through the downstream boundary were removed from the computation. Unfortunately, however, these (upstream and downstream) conditions introduced a systematic error because of the counterflow velocity component, which depended on the free stream velocity[10]. For a flow with Mach number $M_0=5$ the error of the free stream velocity was less than 2%. The problem was surmounted by using a moving piston at the upstream and downstream boundaries whereby the molecules were reflected specularly from the wall of the piston that moved with the free stream velocity. In the calculations nitrogen ($\gamma = 1.4$) with $M_0=4.96$ and $T_0=300\mathrm{K}$ was used as the free stream gas. About 700,000 molecules were used in the simulations. Specular reflection conditions were taken as the boundary conditions at the wedge surface in order to avoid the boundary layer formation which is known to stipulate a change in the shock wave angle of incidence.

The calculations showed that the angles of incidence of the wedge-generated shock waves were close to their corresponding theoretical values (the discrepancy was less than 3%). This small discrepancy is quite understandable owing to an inherent error arising from the fact that the shock wave has a finite thickness of about 10-15 mean free paths. The flow parameters calculated behind the incident shock wave differed from their respective theoretical values by no more than 1%.

The first series of computations was carried out for a set of fixed wedge angles generating incident shock waves with a specified angle of incidence α. A free stream gas flow into which a wedge was instantly inserted at t=0 was used as an initial condition. It was clearly evident that the flow behind the incident shock wave was not uniform for the Kn=0.01 case. Furthermore, for this case the size of the region between the incident shock wave and the leading characteristic of the expansion fan emanating from the trailing edge of the reflecting wedge was only about twice as that

as the shock wave thickness. It was much larger for the Kn=0.004 case for which a uniform flow region was clearly seen.

Rotating wedge simulations were performed in the following way. At the first step a solution for the case $\alpha_i > \alpha_D$, for which only an MR is theoretically possible, was obtained. Then, the computation for $\alpha_{i+1} < \alpha_i$ was performed in such a way that the solution for the case with α_i was used as initial condition for the solving case with α_{i+} . This procedure was repeated until a case with $\alpha_f < \alpha_N$, for which only an RR is theoretically possible, was solved. Then, the direction of the rotation of the reflecting wedge was reversed, and α was increased until the initial value of α was reached. The above procedure ensured that during the rotations from α to α_f and back from α_f to α the $MR \to RR$ and the $RR \to MR$ transitions were encountered, respectively.

The above calculations were performed in two different ways. In the first, as was done by Ivanov et al.[7], the reflecting wedge was rotated around its trailing edge and the gap, g, between the trailing edge and the symmetry plane (see insert in Fig. 1) was kept constant. In the second, the gap was continuously adjusted in such a way that the reflected shock wave passed close to trailing edge of the reflecting wedge but did not hit it. This procedure enabled us to reduce the influence of the expansion wave at large Kn and therefore to reduce the influence of kinetic effects on $MR \to RR$ transition.

Fig. 1 shows the hysteresis loops as calculated using Ivanov et al.[7] (constant gap and an adaptive grid) and our (adjustable gap and a fixed grid) procedures. Ivanov et al.[7] procedure (dashed line) results in $\alpha(RR \to MR) = 39.7^o$ and $\alpha(MR \to RR) = 36.5^o$ in agreement with the value given in their Fig. 5a but not in the text of their paper. The value of these angles as calculated using our procedure (solid line) results in $\alpha(RR \to MR) = 39.7^o$ and $\alpha(MR \to RR) = 35.8^o$. Apparently, kinetic effects caused the difference between the experimental $\alpha(MR \to RR)$ and that obtained by the Monte Carlo simulations. Indeed, the width of the shock wave for Kn = 0.01 was quite large, and the shock wave was even smeared further due to the interaction with the expansion fan. Both these effects did not allow resolving the moment of $MR \to RR$ transition with a reasonable accuracy for Kn values larger than those used both in the present and in Ivanov et al.[7] simulations.

References

1. Ben-Dor, G. (1991), *Shock Wave Reflection Phenomena*. Springer-Verlag, New York.
2. Hornung, H.G., Oertel, Jr. H. and Sandeman, R. J. (1979), Transition from Mach Reflection of Shock Waves in Steady and Pseudosteady flow with and without Relaxation, *J. Fluid Mechanics*, 90, pp. 541-.
3. Hornung, H.G. and Robinson, M.L. (1982), Transition from Regular to Mach Reflection of Shock Waves. Part 2 The Steady Flow Criterion. *J. Fluid Mechanics*, 123, pp. 155-164.
4. Li, H. and Ben-Dor, G.(1996), Application of the Minimum Entropy Production to Shock Wave Reflections. Part 1. Steady Flow, *J. Appl. Phys.*, 80(4), pp. 2038-2048.
5. Chpoun, A., Passerel, D., Li, H. and Ben-Dor, G. (1995), Reconsideration of Oblique Shock Wave Reflection in Steady Flows. Part I: Experimental Investigation. *J. Fluid Mechanics*, 301, pp. 19-35.
6. Vuillon, J., Zeitoun, D. and Ben-Dor, G. (1995), Reconsideration of Oblique Shock Wave Reflection in Steady Flows. Part II: Numerical Investigation. *J. Fluid Mechanics*, 301, pp. 37-50.

7. Ivanov M.S., Gimelshein S.F. and Beylich A.E. (1995), Hysteresis Effect in Stationary Reflection of Shock Waves. *Phys. Fluids*, 7 (4), pp. 685-687.

8. Shirozu, T. and Nishida, M. (1995), Numerical Studies of Oblique Shock Reflection in Steady Two-Dimensional Flows. *Memoirs of the Faculty of Engineering, Kyushu University, Fukurka, Japan*, 55(2), pp. 193-204.

9. Ivanov, M.S., Zeitoun D.,. Vuillon J., Gimelshein S.F. and Markelov G. (1996), Investigation of the Hysteresis Phenomena in Steady Shock Reflection Using Kinetic and Continuum Methods. *Shock Waves*, 5, pp. 341-3469.

10. Bird G.A. (1994), Molecular *Gas Dynamics and Direct Simulation of Gas Flow,* Clarendon, Oxford.

Table 1. Values of the transition angles of the hysteresis loop for $M_0 = 4.96$.

	Theoretical[5]	Experimental[5]	Numerical[7]
$\alpha(MR \rightarrow RR)$	30.9°	30.9°	36.5° *
$\alpha(RR \rightarrow MR)$	39.3°	37.2°	39.7°

*There is a misprint in the text of Ivanov et al.[7] where $\alpha(MR \rightarrow RR) = 35.5^{\circ}$ is quoted.

Oblique Shadowgraph Study of Shock Wave Reflection between Two Wedges in Supersonic Flows

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Over the past few years the interest in the shock wave reflection transition phenomena between two wedges has started to shift away from the study of the criteria necessary in two-dimensional flows to the more practical case with three-dimensional effects. This has been prompted to some extent by the appreciation that in wind tunnel studies the wedges need to have a span less than the tunnel width in order to avoid wall boundary layer interference, and it is thus necessary to examine the extent to which the wedge edge effects can influence the flow at the reflection point. These issues were raised at the last Mach Reflection Symposium by Fomin et al. (1996), and Skews et al. (1996). Estimates of the aspect ratios needed to avoid these effects have been made by Skews (1997). A recent study of considerable interest has been the numerical one reported by Ivanov (1997), that showed that the reflection pattern is more complex that that assumed by Skews in his analysis. In particular, it is shown that a situation can arise (for Mach 5.0) where Mach reflection can exist in the central plane, followed by regular reflection further out, and then by Mach reflection again even further out.

This study uses high-resolution oblique contact shadow imaging to explore a number of these three dimensional effects (at Mach 3.5, which is the limit for the tunnel available). Although no unambiguous confirmation of the above pattern has been obtained additional tests are underway at even larger angles of view so that the reflection at the tunnel center line is clearly visible from the rear. Other interesting features are also seen from these data. These include the locus of the triple point geometry remote from the center line as well as the shape of the stem where it strikes the tunnel window. A number of unexplained patterns when the reflection is of Mach type at the center line are continuing to receive attention. It is expected that the new data will help clarify these issues. This data will be presented.

References

Fomin, W. M., Hornung, H. G., Ivanov, M. S., Kharitonov, A. M., Klemenkov, G. P., (1996), "The study of transition between regular and Mach reflection of shock waves in different wind tunnel", 12th International Mach Reflection Symposium, Skews, B. W. (Ed.), Johannesburg, 137-151.

Skews, B. W., Vukovic, S., Draxl, M., (1996), "Three-dimensional effects in steady flow shock wave reflection transition", 12th International Mach Reflection Symposium, Skews, B. W. (Ed.), Johannesburg, 153-162.

Skews, B. W., (1997), "Aspect ratio effects in wind tunnel studies of shock wave reflection transition", Shock Waves, In press.

Ivanov, M. S., Grimelshein, S. F., Kudryavtsev, Markelov, G. N., (1997), "Transition from regular to Mach reflection in two- and three-dimensional flow", 21st International Symposium on Shock Waves, Great Keppel Island, Australia, In press.

Transition with hysteresis effects between regular and Mach reflection in a 2D supersonic nozzle

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The transition from regular to Mach reflection of shock waves is one of the most challenging problems in shock waves research. In the past two years, considerable advance has been achieved due to numerical [3], [5], [6] and experimental [2], [4] results on hysteresis phenomenon in steady flows predicted earlier by Hornung et *al.* [4] for strong shock waves. Subsequently, numerical simulations of the hysteresis [3] have revealed a variety of physical phenomena involved in this problem. In particular, the existence of hysteresis on the transition RR⇒MR seems due to the effect of the history of the flow. In the present work, the Navier-Stokes simulations of the supersonic flow at the inflow Mach number $M = 5.0$ in a 2D supersonic nozzle with different shock angles have been performed to elucidate the importance of initial data choice and starting process in this problem. Especially, the angles corresponding to the dual solution domain, in which both regular and Mach reflection are theoretically possible, have been considered. The resulting steady flow in the nozzle may be dependent on the choice of initial data and features of the starting process. Such investigation is the objective of the present paper. The numerical scheme, which is second order accurate in space and time, is based on the TVD upwind technique of Montagné and Yee [8]. This scheme is well suited for the problem under consideration because it has property of robust shock capturing and provides good results in smooth regions (shear layer). The analysis of computational grid sensitivity have been performed to isolate physical and numerical features. On figure 1 and 2 we see two different

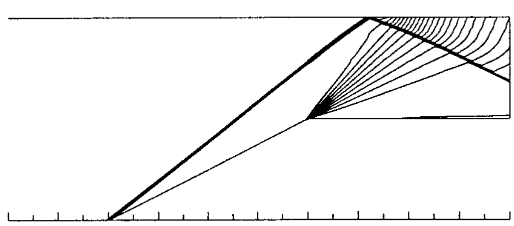

Figure 1: Density contours, steady state solution with regular reflection and uniform initial condition, $t^* = 1.0$.

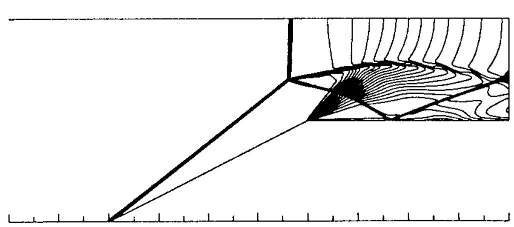

Figure 2: Density contours, steady state solution with Mach reflection and start-up initial condition $t^* = 3.0$.

solutions appearing for the same upstream flow and with the same nozzle geometry. This result illustrates the existance of a dual solution regime for the shock reflection. The difference between the two solutions is due to the start-up conditions (with or without prescribed upstream disturbance). Figure 2 shows also the existence of a slip surface instability that emanates from the triple point and may have influence on the size of the Mach stem and results in its oscillations. Thus, the careful investigation of various aspects of this instability seems important. The obtained results will be presented in more detail in the full-length paper.

References

1. Azevedo DJ, Liu CS, Engineering approach to the prediction of shock patterns in bounded high-speed flows, *AAIA J. 31:83-90, 1993*

2. Chpoun A, Passerel D, Li H, Ben-Dor G, Reconsideration of oblique shock-wave reflections in steady flows. 1. Experimental investigation. *J. Fluid Mech. 301:19–35, 1995*

3. Hadjadj A, Kudryavtsev AN, Ivanov MS, Vandromme D, Numerical investigation of hysteresis effect and slip surface instability in the steady Mach reflection, *21st International Symposium on Shock Waves, Queensland - Australia, July 20-25, 1997*

4. Hornung HG, Oertel H, Sandeman RJ, Transition to Mach reflection of shock waves in steady and pseudosteady flow with and without relaxation, *J. Fluid Mech. 90:541-560, 1979*

5. Ivanov MS, Gimelshein SF, Beylich AE Hysteresis effect in stationary reflection of shock waves, *Phys. Fluids 7:685-687, 1995*

6. Ivanov MS, Gimelshein SF, Kudryavtsev AN, Markelov GN, Numerical study of the transition from regular to Mach reflection in steady supersonic flows, *to be published in Proceedings of 15th Int. Conf. Numer. Meth. Fluid Dyn. (Monterey, USA), 1996*

7. Jackson TL, Grosch CE, Inviscid spatial stability of a compressible mixing layer, *J. Fluid Mech. 208:609-637, 1989*

8. Montagné JL, Yee, HC, Comparative study of high-resolution shock-capturing schemes for real gas, *AIAA J. Vol. 27, No. 10, 1989*

Numerical Studies of Three-Dimensional Effects on the Transition between Steady Regular and Mach Reflections

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The recent numerical and experimental observations of hysteresis phenomenon aroused renewed interest for the problem of the transition between regular reflection (RR) and Mach reflection (MR) of strong shock waves in a steady supersonic flow. Although both experimental and numerical results prove the existence of hysteresis, there are some discrepancies between them, especially concerning the transition angle from RR to MR. The most important reasons for these discrepancies may be the influence of free stream perturbations and three-dimensional effects, both inherent in any experimental facility and not present in 2D computations. In this paper we investigate the impact of three-dimensionality that was certainly considerable in the experiments where the test model with small aspect ratio was used. We simulate the reflection of shock waves generated by two symmetrical wedges or inclined plates at the inflow Mach numbers M = 4 and 5 when, in accordance of two-dimensional gasdynamic theory, RR and MR are equally possible configurations within a broad range of angles of incidence. The computations are performed using two different approaches, continuum (solution of the Euler equations) and kinetic (the DSMC method).

Three-dimensional shapes of shock waves at both regular and Mach reflections were studied. Visualizations of the shock waves as iso-surfaces of gasdynamic quantities were obtained. An unsteady process of the transition between regular and Mach configurations was also investigated. The Mach stem heights obtained in the numerical simulations were compared with experimental data. The following conclusions can be given as a result of the numerical study.

The hysteresis phenomenon can be observed in substantially 3D flows but it has a number of particular features. A decrease of the wedge width/length aspect ratio leads to the delay of the transition from RR to MR.

For RR the spanwise bending of the incident shock wave caused by the finite width of the wedges results in the formation of convex Mach surfaces on the periphery with a supersonic flow behind it.

The MR configuration develops through the formation of a local Mach stem surface in the coreflow. This Mach stem surface increases outwards and merges with the peripheral Mach surfaces. The Mach stem height changes non-monotonically in the spanwise direction.

An excellent agreement is shown between computed and experimental values for the Mach stem height. It has to be noted, though, that even for an aspect ratio of 3.75, a big difference exists between 3D and 2D results.

Influence of Test Model Aspect Ratio in Experiments on the RR $\Leftrightarrow$ MR Transition

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For strong shock waves there exists a range of angles of incidence where both regular and Mach reflections of shock waves are theoretically possible. As a consequence, the transition angle from regular to Mach reflection can differ from the angle at which the reverse transition takes place. This hysteresis phenomenon in the transition between regular and Mach reflections in steady flows was recently observed in both numerical and experimental investigations. Nevertheless, there are significant discrepancies between experimental and numerical results, especially concerning the transition angle from RR to MR. The most important reasons for these discrepancies may be the influence of free stream perturbations and three-dimensional effects, both inherent in any experimental facility and not present in 2D computations. The existing uncertainties in the hysteresis problem encouraged us to continue its experimental investigation and to study the role of three-dimensional effects.

The experiments have been performed in the supersonic wind tunnels T-313 and T-326 of the Institute of Theoretical and Applied Mechanics (Novosibirsk, Russia). T-313 is a blowdown wind tunnel with a 600 mm x 600 mm rectangular test section. The experiments in this wind tunnel have been conducted at the freestream Mach numbers $M = 4$ and 5. At $M = 6$, the experiments have been performed in another facility, T-326, which is a free-jet wind tunnel. A round jet with a diameter of 200 mm exhausts into a vast chamber (the Eiffel chamber). The large size of wind tunnels used made it possible to vary the test model width/length ratio, z/w, in a wide range from 0.66 to 3.75.

The experimental results prove the existence of hysteresis, but it is significantly more obvious for one type of wind tunnel than for the other. The range of incident shock angles where regular and Mach reflection can be optionally observed is very narrow for the blow-down wind tunnel and as much as 3 degrees for the free-jet wind tunnel. Nevertheless, this is considerably narrower than that resulted from numerical simulations. The size of this overlap region seems to depend on the perturbation level because of the instability of regular reflection to large-amplitude perturbations.

A strong influence of three-dimensional effects has been also observed. At small aspect ratios these effects cause a considerable shift of the transition angles to higher values. Moreover, the measured values of the Mach stem height depend on the aspect ration even for z/w larger than 3. Thus, it can be concluded that the aspect ratio required for elimination of three-dimensional effects lies far beyond that previously assumed.

$RR \Leftrightarrow MR$ Transition in Thermochemically Non-Equilibrium Flows

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In a steady flow, as described by Ben-Dor (1992), the wedge-generated shock wave that reflects on a symmetry plane can produce two shock-wave reflection configurations, namely, a regular reflection (RR) and a Mach reflection (MR). Recently, several studies of the $RR \Leftrightarrow MR$ transition in hypersonic steady flow were conducted in order to predict the Mach stem height or the hysteresis phenomenon. However, these studies took into account only aerodynamic and geometric effects (see Vuillon et al. 1995, Vuillon & Zeitoun 1995 and Ivanov et al. 1996). Only Hornung (1979) in an experimental work and Burtschell et al. (1997) in a numerical one have studied the influence of chemical reactions on the $RR \Leftrightarrow MR$ transition behavior.

This last point was the aim of the present work for which numerical simulations have been performed on a wedge at nominal freestream flow Mach numbers larger than five. More particularly, the chemical and thermal non-equilibrium effects on the Mach stem height, the von Neumann and the detachment criteria and the hysteresis effects were investigated.

The two-dimensional supersonic steady flow was computed by solving the unsteady Euler equations. A multi-block finite volume scheme was used with a MUSCL TVD method and an approximate Riemann solver named HLLEMR. The test gas was considered as a mixture of five species resulting from air chemistry.

As preliminary results, an MR configuration in a frozen case for a 29.5° wedge angle and a nominal freestream flow Mach number equal to 7 was simulated. Without changing any parameter and including chemical non-equilibrium effects, the influence of chemistry on the Mach stem height was investigated. The Mach stem was found to be shorter.

The influence of the thermal and chemical effects on the flow behavior will be completely discussed.

References

Ben-Dor, G., "Shock Wave Reflection Phenomena", Springer, New York, U.S.A., 1992.

Burtschell, Y., Cardoso, M., Zeitoun, D. and Abgrall, "Chemical nonequilibrium effects on RR $\Leftrightarrow$ MR transition: Numerical investigations", ISSW21, Australia, 1997, paper 6151A.

Hornung, H. G., Oertel, H. and Sandeman, J., "Transition to Mach reflection of shock waves in steady and pseudosteady flow with and without relaxation", Journal of Fluid Mechanics, 90, 541-560, 1979.

Ivanov, M., Zeitoun, D., Vuillon, J., Gimelshein, S. and Markelov, G., "Investigation of the hysteresis phenomena in steady shock reflection using kinetic and continuum methods", Shock Waves, 5, 341-346, 1996.

Vuillon, J., Zeitoun, D. and Ben-Dor, G., "Reconsideration of oblique shock wave reflection in steady flows. Part 2: Numerical investigation", Journal of Fluid Mechanics, 301, 37-50, 1995.

Vuillon, J. and Zeitoun, D., "Numerical investigations on the prediction of the Mach stem height in steady flows", Shock Waves@Pasadana, ISSW 20th, 1995.

Real Gas Effects on Shock Reflection in Steady Hypersonic Flows

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Two types of shock wave reflection are possible in steady flows, regular and Mach reflections. There are two principal criteria of the transition between these reflections. The first is the detachment criterion that determines the upper boundary of existence of regular reflection (RR), and the second is the von Neumann criterion that states the bottom limit where Mach reflection (MR) can exist. For an angle of incident shock wave, α, that lies between these boundaries, in the so-called dual solution domain, both Mach and regular reflections are theoretically possible. The difference between the transition angles, corresponding to the detachment, α_D, and von Neumann, α_N, criteria approaches 10 degrees when the Mach number is more than 5.

The dependence of the transition angle on the direction of the shock angle variation was actively studied from the mid 70s to the mid 80s, mostly by experimental methods. The results of such experimental investigation were summarized in [1] as follows: transition from RR to MR and back in steady flows takes place according to von Neumann criterion; in the dual-solution domain RR is unstable and a hysteresis effect, i.e. a dependence of reflection type on the direction of the incidence angle variation, was not observed. However, new numerical studies [2] revealed a possibility of such a hysteresis to exist. Moreover, the hysteresis was experimentally established [3], though under conditions different from experiment [1]. Further studies were also performed [4] and the results of computations that examined the transition criteria with two different approaches -- continuum and kinetic were presented.

All the work that was carried out in the field of steady shock wave reflection phenomena is limited to the case of one-species non-reactive gas. As for the flow of chemically reactive gas mixture, this topic presently has not been studied enough. This paper will therefore fill the lack of information and knowledge on steady shock wave reflection in reactive flows.

The principal goal of this work is to study the impact of high-temperature real gas effects, i.e. excitation of vibrational mode and chemical reactions, on regular and Mach configurations and on the transition between two reflection types. A detailed comparison of results with and without real gas effects will be presented. The study of the problem of shock wave reflection in steady reactive flows has an obvious theoretical as well as practical interest that is connected to hypersonic flight of spacecraft. In fact, the paper is a first attempt to examine this problem.

The main approach used here is the Direct Simulation Monte Carlo (DSMC) method. An important advantage of this method is that it accounts for viscosity, and the thickness of the shock waves is physically grounded. Lately this method has been commonly used for calculating near-continuum flows as an alternative for the finite-difference approach. Moreover, the DSMC models for real gas effects proposed lately enable us to obtain reliable data on high-temperature flows in the near-continuum regime.

A special numerical approach combining cell and free cell majorant frequency schemes of the DSMC is used in computations [5] in order to provide an adequate space resolution in the entire computational domain. The transitions between the translational and vibrational molecular modes are simulated with a model based on the quasi-classical approach [6], one of the most effective techniques to describe the energy exchanges between the translational and internal modes. Both vibration-translation and vibration-vibration energy exchanges are considered in this model. Chemical reactions are treated with a model that includes the effect of vibration-dissociation coupling by using specific chemical reaction rate constants for each vibrational level [7].

The main topics of the work are the following:

1. Determination of the applicability area of the transition criteria. The computations of both monatomic and diatomic non-reactive gases (specific heat ratio, γ, was 1.66 and 1.4) showed that in these flows the reflection type depends on the direction of the incidence angle variation, coming from below and from above the dual solution domain. When increasing the angle, the transition from RR to MR occurs in accordance with the detachment criterion, and the reverse transition is observed at the von Neumann criterion when decreasing the angle. The computed transition angle of the wedge-generated shock wave were found to correspond to their theoretical values α_N and α_D obtained from the inviscid gasdynamic. Meanwhile, the vibrational excitation and chemical reactions cause a reduction of the effective γ and, therefore, a reduction of the incident shock wave angle. The effective γ is also changed in the flow depending on the local temperature. The transition angle between RR and MR is determined by the angle of the incident shock wave near the reflection point.

2. The problem of hysteresis phenomena is closely connected with the first topic. As was mentioned above, a hysteresis and a dependence of the final reflection type on the initial condition was observed in the DSMC simulations of non-reactive gases. The results of computations for a gas with high-temperature real effects will be presented in the full-length paper.

3. The influence of the Knudsen number on the shock configuration (in particular, on the Mach stem height) is an important problem as well. The computation manifested a decreasing of the Mach stem and an earlier transition from MR to RR when increasing the Knudsen number for non-reactive gases. Real gas effects complicate considerably this phenomenon, since the size of relaxation zone is comparable with the characteristic size of the flow even for very small Knudsen numbers.

References

1. Hornung, H. G. and Robinson, M. L., (1982), "Transition from regular to Mach reflection of shock waves. Part 2. The steady low criterion", J. Fluid Mech., 1299, 155-164.

2. Ivanov, M. S., Gimelshein, S. F., Beylich, A. E., (1995), "Hysteresis effect in stationary reflection of shock waves", Phys. Fluids 7(4), pp. 685-687.

3. Chpoun, A., Passerel, D., Li, H., Ben-Dor, G., (1995), "Reconsideration of oblique shock wave reflections in steady flows", J. Fluid Mech., 301, pp.19-35.

4. Ivanov, M., Zeitoun, D., Vuilon, J., Gimelshein, S., Markelov, G., (1996), "Investigation of the hysteresis phenomena in steady shock reflection using kinetic and continuum methods", Shock Waves 5(6), pp. 341-346.

5. Ivanov, M.S., Antonov, S. G., Gimelshein, S.F., Kashkovsky, A.V., (1994), "Computational tools for rarefied aerodynamics", Proc. XVII Intern. Symp. on Rarefied Gas Dynamics, Vancouver, Canada, Vol.160, pp. 115-126.

6. Gimelshein, S.F., Gorbachev, Yu.E., Ivanov, M.S., Kashkovsky, A.V., (1995), "Real gas effects on the aerodynamics of 2D concave bodies in the transitional regime", Proc. XIX Intern. Symp. on Rarefied Gas Dynamics, Oxford University Press, Vol. 1, pp. 556-563.

7. Gimelshein, S., Gorbachev, Yu., Ivanov, M., Markelov, G., (1997), "Statistical simulation of non-equilibrium rarefied flows with quasi-classical VVT transition models", Atlanta, AIAA Paper 97-2585.

Comparison between computational and theoretical results of Li and Ben-Dor on supersonic 2D jets

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The aerodynamic study of supersonic exhaust jets is one of the most challenging problem in space and aeronautical applications. The various physical phenomena involved in these fluid dynamics problem are linked directly to the performances of the engines. For nozzles operating under higly over-expanded flow conditions, the shock generated at the edge of the nozzle is so strong that a regular reflection from the centerline is not possible, and Mach reflection occurs. Referring to figure 1, where a typical Mach reflection is depicted, somewhere along the straight incident shock I, a triple point T appears. A reflected shock R which may be strong and a Mach stem MS which is a curved strong shock are initiated from the triple point along with a slip line S indicating the entropy discontinuity.

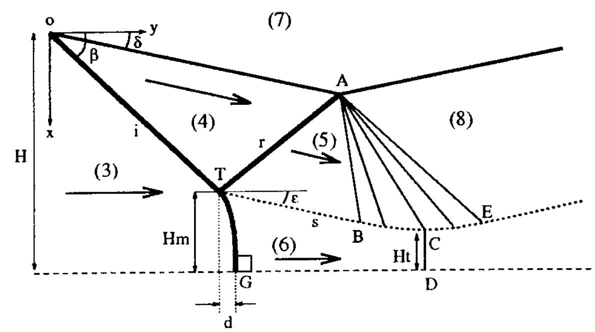

Figure 1: Schematic illustration of Mach reflection from over-expanded nozzle flow

During the last thirty years experimental set-ups have been widely used to simulate Mach reflection associated with over-expanded nozzle free jet flows [13]. Several empirical correlations have been established to predict such flow topology [1], [2], [4], [9], [10]. Nevertheless, the Mach reflection mechanism is quite complex and not yet clearly understood. Indeed, much of the prediction theories of shock wave reflection based on fundamental knowledge of free jet flows is still need.

Recently, Li and Ben-Dor [12] have developed a new model which is based on two- and three-shock theories. This model explains how and when a Mach stem is formed from a 2D jet and accounts for the more realistic situation in which the Mach stem is curved. The present paper aims to reproduce, via numerical simulation, the over-expanded nozzle free jet flow structure and compares the numerical results with the aforementioned model [12].

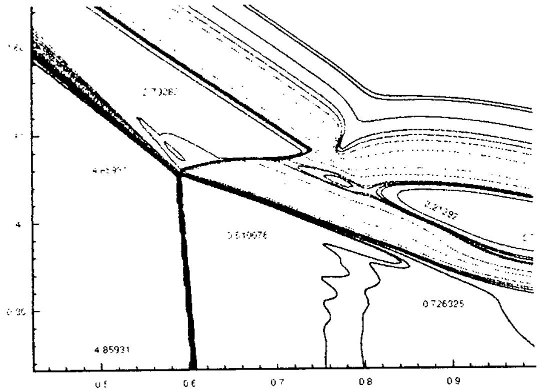

Figure 2: Numerical results of the over-expanded jet with Mach reflection. Iso-Mach contours

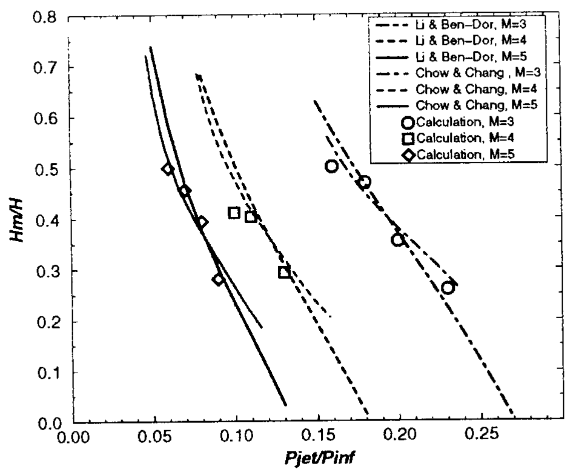

Figure 3: Dependence of the non-dimensional Mach stem height, Hm/H, on the pressure ratio, P_{jet}/P_{inf}

The flowfield is simulated by solving 2D Navier-Stokes equations for compressible laminar flow. The governing equations are solved by an explicit time-dependent finite volume technique including flux-splitting formulation [11]. Adaptative mesh grid refinement has been used for better shock capturing. Some of the computational results are presented here. For example, figure 1 depicts a snapshot of the triple point configuration with a subsonic region downstream of the Mach stem. The location and the size of the Mach stem occurring within such flowfield have been examined. Excellent agreement has been obtained between the theoretical and numerical results for Mach reflection of the 2D jet (see figure 3). The obtained results will be presented in more detail in the full-length paper.

References

1. Abbett, M., The Mach disc in underexpanded exhaust plumes, *AIAA J., Vol. 9, No. 3, March 1971, PP 512-514*

2. Nicholls, J.A., On the structure of jets from highly underexpanded nozzles into still air, *JAS, 26, 1, 1959, pp 16-24*

3. Azevedo, D.J. and Shi Liu, C., Engineering approach to the prediction of shock patterns

in bounded high-speed flows, *AIAA Journal, Vol. 31, NO. 1, pp 83-90, 1993*

4. Back, L.J. and R. F. Cuffel, R.F., Viscous slipstream flow downstream of a centerline Mach reflection, *AIAA Journal, Vol. 9, NO. 10, Oct. 1971*

5. Ben-Dor, G., Reconsideration of the three-shock theory for a pseudo-steady Mach reflection, *Journal of Fluid Mechanics, Vol. 181, pp 467-484, 1987*

6. Ben-Dor, G., Shock wave reflection phenomena, *Ed. Springer-Verlag, 1992*

7. Bleakney, W. and Taub, A.H., Interaction of shock waves, *Rewiews of Moderns Physics, Vol. 21,No. 4, 1949*

8. Bowyer, J., D'Atorre, L. and Yoshihara, H., The flow resulting from Mach reflection of a convergent conical shock axially symmetric jet, *GDA 63-0586, General Dynamics, Astronautics, 1963*

9. Chow, W.L. and Chang, I.S., Mach reflection associated with over-expanded nozzle free jet flows, *AIAA Journal, Vol. 13, NO. 6, pp 762-766, 1975*

10. Eastman, D.W. and Radtke, L.P., Location of the normal shock wave in the exhaust plume of a jet, *AIAA J., 1, 4, 1963, p. 919*

11. Hadjadj, A., Analyse Physique et simulation numérique des écoulements compressibles, application aux tuyères de propulseur, *Ph.D. Thesis, University of Rouen, 1997*

12. Li, H. and Ben-Dor, G., On the reflection wave configurations in supersonics jets of over-expanded nozzles, *J.F.M., 1997*

13. Love, E.S. and Grigsby, C.E., Experimental and theoretical studies of axisymmetric free jets, *NACA, R6, 1959*

Numerical Study of Shock Reflection Hysteresis in an Underexpanded Jet

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1 Introduction

Underexpanded jets are found in a number of applications, for example rocket exhausts at high altitude, vehicle manoeuvring thrusters, propulsion simulation devices and fuel injectors. Although the use of underexpanded jets is clearly of real industrial interest, their detailed structure and mechanisms are not yet fully understood. Quantitative experimental investigation of this problem, aside from being expensive, suffers from probe interference with the jet structure, necessitating the development of non-intrusive measurement techniques [1]. However, these promising methods have yet to reach full maturity and the potential of a CFD analysis is clear.

The sudden expansion of the free jet from a nozzle initiates a complex flow field involving the interaction of an expanding core flow, compression wave reflection at the jet boundary and shock wave reflection at the centre-line. A characteristic of this type of flow is a repeated "shock bottle" or "barrel shock" pattern. The shock reflection at the centre-line can take two forms, regular or Mach reflection, the latter associated with higher pressure ratios. The basic characteristics of an underexpanded jet with Mach reflection are described in [2]. More recently, Welsh [1] reports a hysteresis effect in the shock reflection type in a (laminar) nitrogen jet exhausting from a nominally Mach 3 nozzle. In a CFD study the crucial quantities of upstream Mach number and incident shock angle are inherent parts of the calculation. All of the interacting features of the complex flow field must be resolved accurately, making this a demading problem.

2 Flow Solver

For full details consult [3],[4]. The axisymmetric Navier-Stokes equations are solved using a cell-centred finite volume method employing Osher's scheme and MUSCL variable interpolation. The linear system arising at each implicit time step is solved using a Generalised Conjugate Gradient method with BILU preconditioning and approximate Jacobians.

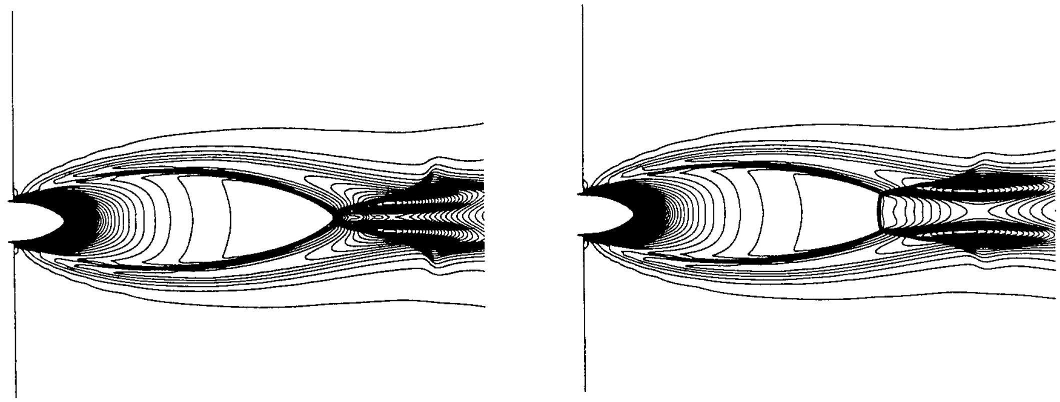

Figure 1: Density contours showing regular (left) and Mach reflection, $P_o/P_b = 285.7$

3 Results

Calculations were performed over a range of pressure ratios from well inside the regular reflection range to well inside the Mach reflection range including the hysteresis loop. A quasi-steady approach was employed in order to account for time history effects. First, converged solutions were obtained for the conditions at the extremeties of the range of interest. These were used as initial solutions for a calculation with a small change in pressure ratio, thus beginning to traverse the range, this solution being used subsequently as the next initial solution etc. By using a small step change in pressure ratio between calculations this approach is very robust and converges quickly at each condition. The hysteresis effect in the shock reflection type was predicted in accordance with experimental observations. Good agreement with experimental data will be demonstrated. The detail obtained from CFD analysis has identified several interesting aspects of the plume structure which will be discussed. Figure 1 shows calculated density contour plots indicating regular and Mach reflection patterns for the same conditions.

References

[1] F.P. Welsh, "Shock Reflection Hysteresis in Low Density Under-Expanded Jets", *DRA Technical Report DRA/DWS/WX9/CR97361,* March 1997.

[2] S. Crist, P.M. Sherman and D.R. Glass, "Study of the Highly Underexpanded Sonic Jet", *AIAA Journal, vol 4, No 1, pp. 68-71,* 1966.

[3] F. Cantariti, M. Woodgate, K.J. Badcock and B.E.Richards, "Approximate Jacobians for the Euler and Navier-Stokes Equations", *University of Glasgow, Aero Report 9705,* 1997.

[4] K.J. Badcock, W. McMillan, M.A. Woodgate, B.J. Gribben, S. Porter and B.E. Richards, "Integration of an Implicit Multiblock Code into a Workstation Cluster Environment", *Parallel Computational Fluid Dynamics: Algorithms and Results using Advanced Computers, P. Schiano et al. (Eds.), Elsevier Science B.V. Amsterdam, 408-415,* 1996.

An Analysis on Predicting Stem Heights in Inlet Flow Mach Reflections

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An analytical investigation of Mach reflections is conducted in high speed inlet flows for the purpose of predicting stem heights. The solution sought is based on a control volume that is defined inside a double wedge inlet configuration that is streamwise symmetric. Of particular interest is the dependency of the Mach stem on both the inlet height and the von Neumann angle. The integral form of the governing equations is applied to the control volume and the analysis is carried out for an ideal gas assuming steady, inviscid flow with no downstream influences. The Mach stem is treated as a normal shock with no curvature with respect to the freestream. The assumption of a zero pressure gradient across the slipstream reduces the problem to a three by three linear matrix. For wave angles near the von Neumann angle the explicit solution is found to have the form of the similarity model. The analytical model is compared to experimental data for M_∞=4.96, 3.98, 3.49 and 2.84. The results from this investigation agree favorably with both the experimental data as well as with numerical calculations based on the Navier-Stokes equations done in previous studies. It is concluded that Mach stems are independent of downstream parameters and have a linear dependency to the von Neumann angle and inlet height but an inverse relation with freestream Mach number.

The Principle of Minimum Entropy Production Applied to Inverted Mach Reflection and Shock Reflection Hysteresis in Steady Flow

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1 Introduction

The principle of minimum entropy production [1] states that if more than one steady state solution is compatible with the problem boundary conditions then nature prefers the solution of minimum dissipative structure i.e. the observed solution is that with the minimum rate of entropy production. The principle has been applied to the deflection of supersonic flow by wedges to explain the prevalence of 'weak' over 'strong' shock solutions [2],[3]. It can be easily demonstrated that the 'strong' solutions incur a greater entropy production rate, and hence the principle explains why the 'weak' solution is the one normally observed. As noted by Salas [3], the principle does not disprove the possibility of a 'strong' shock solution if the downstream pressure is given as a boundary condition. The principle of minimum entropy production applies only when multiple steady states occur which satisfy the same boundary conditions. Thus in this case for a fixed upstream Mach number and flow deflection angle the principle indicates the 'weak' solution, but if the downstream pressure is given as a boundary condition then the boundary condition set has changed and the 'strong' solution may occur. An analogous situation is that of regular reflection where oblique shock theory indicates 'weak' and 'strong' solutions and the principle explains the prevalence of the 'weak' solution in experiment [2]. Pseudo-steady shock reflection has also been examined in this way [4]. Thus a precedent clearly exists for using the principle of minimum entropy production to help explain phenomena associated with shock wave reflections. Encouraged by this, in the present work the principle is applied to Inverted Mach reflection (IMR) and shock reflection hysteresis (SRH) in steady flow in an attempt to explain the experimental observations.

2 Steady Inverted Mach Reflection

The von Neumann condition has been accepted as the lower pressure limit to the dual solution domain in steady shock reflection. However, examination of pressure-deflection diagrams indicates that in theory Mach reflection may continue past this point, the reflection becoming *Inverted*, the flow through the triple point being deflected away from the reflecting surface or symmetry line. It can be shown that the entropy increase across both the oblique and Mach stem parts of an IMR is greater than that across a corresponding RR. Since the total mass flow rate must be

equal for both cases then the IMR has the greater associated entropy production rate. Thus the principle of minimum entropy production explains why IMR is not normally observed and RR prevails. It will be demonstrated how the possibility of suppressing RR to obtain IMR does not violate this conclusion.

3 Steady Shock Reflection Hysteresis

A large number of relatively recent experimental and numerical studies have contributed to the understanding of steady shock reflection hysteresis. However, the information condition of Hornung[5] appears to explain the persistence of RR only; to the authors' knowledge it has not been explained why MR should persist in preference to RR for the other half of the hysteresis loop. The persisitence of MR is examined using the principle of minimum entropy production. Due to the additional geometric complexity of the three shock system this requires reliance on some assumptions and quantification based on experimental observations[6]. The analysis suggests that MR persists since the associated rate of entropy production is less than that of the equivalent RR. This leads to a reconsideration of the SRH problem as a whole.

References

[1] P. Glansdorff and I. Prigogine, "Thermodynamic Theory of Structure, Stability and Fluctuations", *Wiley-Interscience, U.K.* 1971.

[2] H. Li and G. Ben-Dor, "Application of the Principle of Minimum Entropy Production to Shock Wave Reflections. I. Steady Flows", *Journal of Applied Physics, vol 80, No 4, pp. 2027-2037,* 1996.

[3] M.D. Salas and B.D. Morgan, "Stability of Shock Waves Attached to Wedges and Cones", *AIAA Journal, vol 21, No 12, pp. 1611-1617,* 1983.

[4] H. Li and G. Ben-Dor, "Application of the Principle of Minimum Entropy Production to Shock Wave Reflections. I. Pseudosteady Flows", *Journal of Applied Physics, vol 80, No 4, pp. 2038-2048,* 1996.

[5] H.G. Hornung, "Regular and Mach Reflection of Shock Waves", *Annual Reveiw of Fluid Mechanics, vol 18, pp. 33-58,* 1986.

[6] A. Chpoun, D. Passerel, H. Li and G. Ben-Dor, "Reconsideration of Oblique Shock Wave Reflection in Steady Flows. Part I: Experimental Investigation", *Journal of Fluid Mechanics, vol 301, pp. 19-35,* 1995.

Analytical and Experimental Investigations of the Reflection of Asymmetric Shock Waves in Steady Flows

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The reflection of asymmetric shock waves in steady flows is studied both theoretically and experimentally. In addition to regular and Mach reflection wave configurations, an inverse-Mach reflection wave configuration, which has been observed so far only in unsteady flows (e.g., shock wave reflection over concave surfaces or double wedges) has been recorded in steady flow reflections for the first time. The hysteresis phenomenon that exists in the reflection of symmetric shock waves in steady flows has been found to exist in the reflection of asymmetric shock waves. The domains and transition boundaries of the various types of overall wave reflection configurations are analytically predicted. The analytical findings have all been confirmed and verified by the experimental study.

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